EXTREME HIGH BRIGHTNESS ELECTRON BEAM GENERATION IN A SPACE CHARGE REGIME

A. Bacci, L. Faillace, M. Rossetti Conti* INFN-Mi, 20133 Milano, Italy
*also at Università degli Studi di Milano, 20133 Milano, Italy

Abstract

The generation of ultra-short, low emittance and low energy spread electron bunches is nowadays a critical requirement for accelerators in plasma wave or for femtosecond light sources. A new longitudinal compression scheme, based on velocity and ballistic bunching techniques in presence of space charge forces, allows to enter in a peculiar regime, so-called laminar bunching (LB). In this regime, the bunch is longitudinally compressed, at the expense of its transverse size, and the over-bunching is forbidden by the laminarity: going to the minimal longitudinal dimension the bunch is adiabatically frozen and transversally refocused. Furthermore, this technique heats slightly the uncorrelated energy spread resulting in electron distributions that, in case of bending paths, does not require Laser Heater devices.

INTRODUCTION

In the last decade the production of ultra-short electron bunches has become a major item in many fields that are related to accelerating machines. One of the main application interested in such kind of beams is the Free Electron Lasers (FELs) with the aim to produce ultra-short light pulses, femtosecond orders, to explore ultra-fast phenomena like chemical reactions or phase transitions. A typical example is the study of the water splitting in the photosynthesis that ranges from 1 up to 100 fs [1]. Other technologies pursuing ultra-short electron bunches are the plasma wave acceleration [2-5], the femtosecond electron diffraction FED [6] and the coherent THz transition radiation [7].

There are many techniques to longitudinally compress electron bunches. Basically all these techniques are based on a linearly correlated energy spread (linear chirp) given along the distribution and accordingly on the velocity differences of the particles which return in to the compression effect. The compression is performed along a drift in terms of time of flight (ballistic bunching [8, 9]) or along a dispersive line, in terms of different paths length (magnetic chicanes) [10]. An alternative compression technique, named Velocity Bunching (VB) [11], occurs inside a traveling wave (TW) accelerating cavity, where the beam is accelerated and chirped at the same time. The VB technique operates at low energies, typically electron guns exit energies which are lower than 7 MeV. In order to prevent the emittance degradation, the laminarity of the beam, which permits to damp the emittance oscillations during the compression, has to be preserved. This laminarity beam condition is kept propagating the beam as close as possible to an equilibrium invariant envelope, representing an exact solution of the envelope equation, that is obtained by the following conditions: inject in to the compressor with a laminar envelope waist ($\sigma' = 0$), a compression factor that scale linearly with the acceleration $I = \frac{\gamma}{\gamma_0} I_0$ where I stands for the current, γ for the relativistic factor and the index 0 for values before the compression.

The VB is a technique used, or tested, worldwide in different labs and nowadays it is a reference technique to compress electron beams at low energy. Typical VB performances, easily reached, are peak beam currents approaching, or overcoming, 1 kA and emittance values lower than 1 mm-mrad for bunch charge of few hundreds of pico-coulombs and final energies of 80-100 MeV [12]. These high brightness bunches generated by VB show the common characteristics to have a spike current on the bunch head, where most of the charge is stacked and a long low charge tail. The beam quality of the tail is usually poor, shown a very high energy spread, which is a peculiarity of the VB itself where the compression is obtained at the expense of the energy spread, then damped by the acceleration.

In this work is presented a new compression technique that permits to compress an electron bunch in an almost uniform way, if compared to the VB and, at the same time, to quasi fully compensate the bunch energy spread. This method takes advantage from a space-charge dominated regime and because most of the compression happens along a drift, where the bunch is laminar, under the effect of its only field, it has been named laminar bunching LB. In the following paragraph is presented an ideal machine layout to perform the LB and discussed it beam dynamics, considering the longitudinal and the transversal envelop equations. At the end of the proceeding is presented a comparison between the VB and the LB from simulations point of view and from the different evolutions of the envelope equation self-fields terms.

LAMINAR BUNCHING

The LB machine layout presented in this work is as follows (Fig. 1): 1.6 cells s-band photoinjector coupled to a solenoid for the emittance compensation; a drift of about 1.3 meters; a x-band TW 9 cells accelerating cavity, which is used in decelerating mode; a s-band 3 m long, SLAC type, accelerating cavity embedded into a solenoids array; a quite long drift, about 3 m long, where the electron bunch enters into the LB; a couple of equal TW c-band accelerating cavities, 114 cells, 2 meters long, that boost the beam.

For sake of a better LB beam dynamics understanding let us start analyzing transverse and longitudinal envelope equation, respectively Equations (1) and (2):
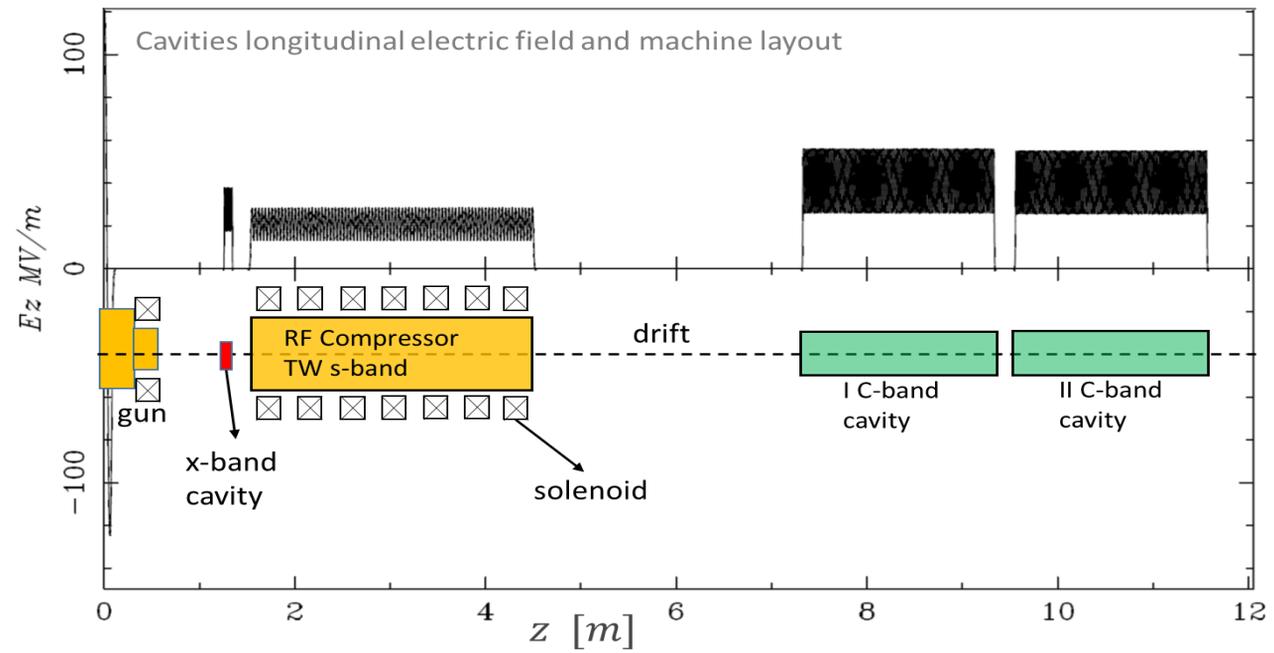
Figure 1: The machine layout used for the laminar bunching simulations and the longitudinal fields intensity of the different cavity involved in the new compression method. The gun is a standing wave accelerating cavity, the other cavities work in traveling wave.

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \left(\frac{k}{\gamma}\right)^2 \sigma = \frac{Qc}{2I_A\gamma^3\sigma_z\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma} \qquad (1)$$

where σ is the rms beam envelope, γ the Lorentz factor, $\gamma' \approx 2E_{acc}$, E_{acc} [MV/m] being the accelerating field, $k = \frac{eB_{SOL}}{mc}$ the solenoid focusing strength, considering negligible the rf ponderomotive focusing force, B_{SOL} the field intensity of the solenoids around s-band TW structure, $I_A = 17kA$ the Alfvén current and ε_n the normalized rms transverse emittance.
The longitudinal envelope equation can be written as follows:

$$\sigma_z'' + K_z\sigma_z + \frac{\gamma'\sigma_z'}{\beta^2\gamma} = \frac{I}{I_A\beta^2\gamma^4\sigma} + \frac{\varepsilon_z^2}{\beta^2\gamma^6\sigma_z^3} \qquad (2)$$

with σ_z the rms bunch length, β the normalize velocity, ε_z the normalize rms longitudinal emittance, σ the rms bunch transversal dimension $\sigma = \sigma_x = \sigma_y$ (which couples the two envelope equations Eq. (1) and Eq. (2)), $\gamma_0' = \frac{eE_{acc}}{m_0c^2}$ the normalized acceleration gradient and K_z the RF longitudinal strength:

$$K_z = \frac{4\pi\gamma_0'\sin|\varphi_0(z)|}{\lambda_{RF}(\beta\gamma)^3} \qquad (3)$$

with $\varphi_0(z) = \frac{z}{c}\left(1 - \frac{\gamma}{\sqrt{\gamma^2-1}}\right)$ (maximum acceleration at $\varphi_0 = 0$).
The third term on the left of Eq. (2) is a velocity damping term, always in contrast with focusing or defocusing. The

last two terms, on the right hand of the same equation, represent internal forces and are respectively the space charge and the emittance longitudinal pressure, from which is possible to define the longitudinal laminar parameter ρ_z:

$$\rho_z = \frac{Qc(\gamma\sigma_z)^2}{I_0\sigma_x\varepsilon_z^2} \qquad (4)$$

This parameter provides a value of the bunch laminarity and also of the bunch stiffness with respect to the compression. The laminarity is guarantee for values greater the one ($\rho_z > 1$), which is a typical condition during compressions at low energy (VB or LB), differently for overcompression regimes, where the laminarity is lost (next paragraph). The stiffness of the bunch versus the compression decreased for ρ_z approaching the unity, favoring a more effective compression process.

A description of the LB beam dynamics, following the Fig. 1 layout and showing in advance some results of the simulations paragraph, is as follows:

- The bunch exiting from the gun, with an energy of 5.9 MeV, under the effect of the gun-solenoid and being space charge dominated, undergoes the emittance compensation process along a drift [13]. So far the dynamics is known, equal to many other low emittance injectors.
- Downstream the drift the bunch enters into a short, high frequency (x-band) accelerating cavity (see the paragraph: RF SYSTEM), that decelerate the bunch of 2.3 MeV. This deceleration that bring the bunch at the low energy of 3.6 MeV has many important effects: 1) it strengthens the long. space charge effects, also if

the long. laminarity decreases, favouring a faster compression; 2) moves the bunch spike current on the bunch tail pre-compensating the symmetric VB effects (Fig. 2 and 3), resulting in a much more uniform charge distribution at the compression end; 3) provides a pre-compression; 4) it enlarges the envelope relaxing transversal space charge effects; 5) applies a pre-correction of the radio rf curvature (Fig. 3, upper plot); 6) the energy decreasing results in an larger bunch vs. rf-phase slippage, a key effect for the VB technique.

- After the high harmonic cavity, the bunch is injected into a typical cavity for the VB where it is chirped (in the longitudinal phase-space), compressed and accelerated.

- Downstream the VB cavity there is a long drift where the bunch enters at about 20 MeV and the full effectiveness of the LB takes place, region highlighted in Fig. 4. The beam propagates under the effects of its own fields and of the momentum distribution at the VB cavity exit. The resulting beam dynamic is peculiar: an envelope that grows linearly (in first approximation) and a bunch length σ_z that decreases following a hyperbolic trend (Fig. 4, zoomed box). This behaviour shows to be in balance and the compression can be pushed at very high values, at the expense of the envelope enlargement. The peculiar equilibrium of the LB, compression versus enlargement, going forward in the drift at some point is lost. The beam parameters to check are the energy spread σ_E and the transverse normalized emittance ε_n, the first is wonderfully damped by the longitudinal space charge effect (Fig. 4, lower plot), while the second, i.e. the ε_n, ends a long chromatic oscillation, closing the bow tie distribution of the transverse phase space (Fig. 4, lower plot). The bunching can be frozen by boosting the beam, when the emittance and energy spread are fully damped. The final result is impressive as reported in the next paragraph, where it is shown a longitudinal phase space of a bunch almost homogeneous in charge, with a spike current close to the central position and with an energy spread comparable to the one at the gun exit (below 100keV for the whole bunch, below 20 keV for the spike current). The energy spread, initially responsible of the compression, is quasi completely cancelled by the space charge effect. Furthermore, the space charge dominated regime heats the uncorrelated energy spread, which can be an important advantage for applications needed laser-heater devices (typically FEL).
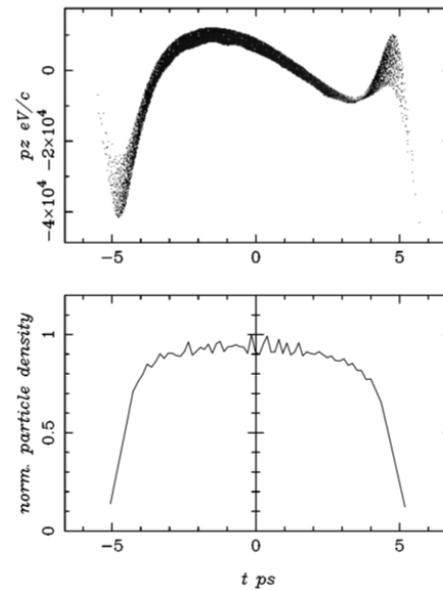
Figure 2: The upper plot is the beam Longitudinal phase space, at 1 m from the cathode, i.e. before entering in the high harmonic cavity. It is visible the rf curvature inherited from the gun. The lower image is the particle density along the bunch.
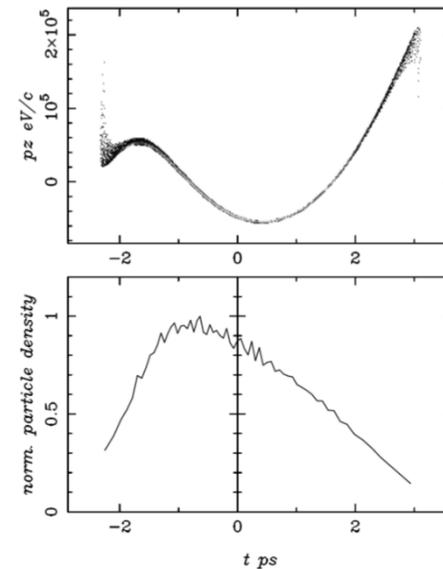
Figure 3: The upper plot is the beam Longitudinal phase space, at 2 m from the cathode, i.e. after the high harmonic cavity. It is visible the rf curvature correction (and pre-correction). The lower image is the particle density along the bunch; It is well shown the effect of the decelerating x-banc cavity, which pre-correct the current distribution by moving charge on the bunch tail.
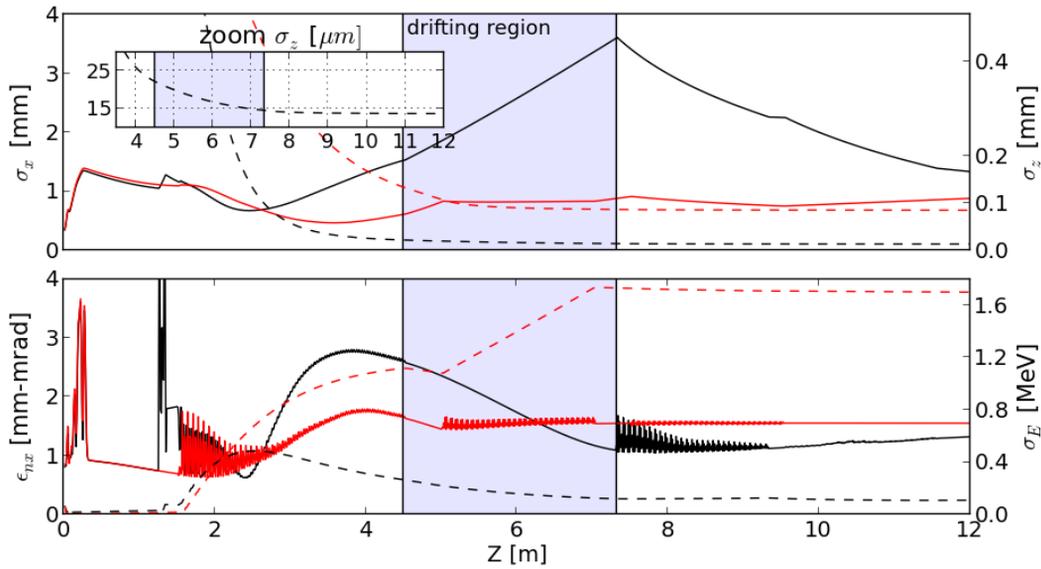
Figure 4: VB and LB comparison for simulations that aim to maximize the bunch brightness. In red are reported the VB results, in black the LB ones. The upper plot reports the envelopes (solid lines) and the bunch lengths (dashed lines), in the box is zoomed the bunch length for the LB case, to highlight the hyperbolic trend along the drift. The lower plot reports the emittances (solid lines) and the bunch energy spreads (dashed lines).

SIMULATIONS

In this paragraph is presented a comparison between two different compression methods, the VB and the LB. The both have been optimized, on the bunch brightness, by using the genetic algorithm GIOTTO [14,15], and the particles track have been done by using the code ASTRA [16]. The aim is not that to show what compression technique is better, but to outline the peculiarities of the LB (a new technique here proposed), versus a known technique, that as the VB, bunches linearly and works in the same energy range. Indeed, the two methods are relatives, but their final results are quite different. As we pointed out above, the VB, pushed at high compression values, favors a single spike compression, on the bunch head, differently the LB works almost on all the bunch charge, therefore also if the spikes current, at maximum compression, for both VB and LB can be equal (or quasi), the rms computed values can be very different, e.g. the compression factor ($\sigma_{z,i}/\sigma_{z,f}$) into Fig. 5.

The layout used for the LB is shown and described in the previous paragraph (Fig. 1). The VB layout is very close to the LB one, however with the following differences: the x-band cavity is missing; the long drift is missing and soon after the s-band cavity the bunch is frozen in terms of compression and emittance compensation (a c-band booster in place of the LB drift).

Figure 4, the upper plot, reports the invariant envelopes (red curve) typical of the VB technique. For sake of completeness the Fig. 5 reports also a VB case where, after the s-band cavity, the booster is removed and the bunch enters into a LB drift like. Along this drift the bunch goes straight into the over compression regime (Fig. 5 upper plot, cyan curve), and, here not reported, the emittance compensation is completely lost. It is interesting to note the ρ_z parameter that, because the VB beam conditions are different than for

the LB case, the laminarity is lost (Fig. 5, lower plot, cyan curve: $\rho_z < 1$), giving the over compression and beam qualities degradation. The ρ_z is also a measure of the beam reaction to the compression and in the lower plot of the Fig. 5, the black curve shows the benefit of the high harmonic cavity, that drops down the beam laminarity, keeping it $\rho_z > 1$, with favors the compression, compensate the energy spread and prevent bunch slices overlapping.
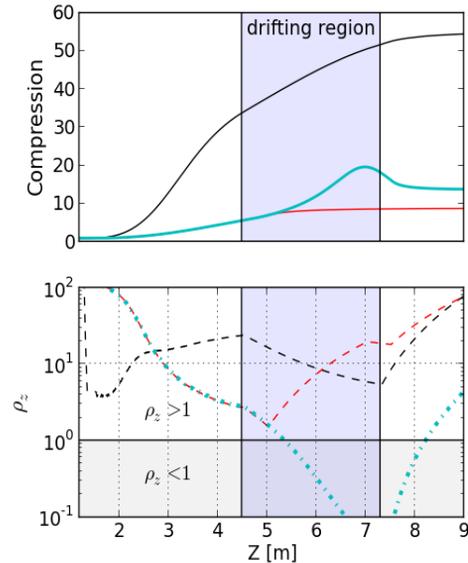
Figure 5: The upper plot reports the compression factor for the LB case (in black), the VB case in red and a VB test case (in cyan) where, after the s-band cavity, the bunch travels a drift, rather than being boosted. The lower plot reports the relative laminar parameters (Eq. (4)).

Figures 6 and 7 show the longitudinal phase spaces and the slices bunch current, respectively for the VB and LB simulations.
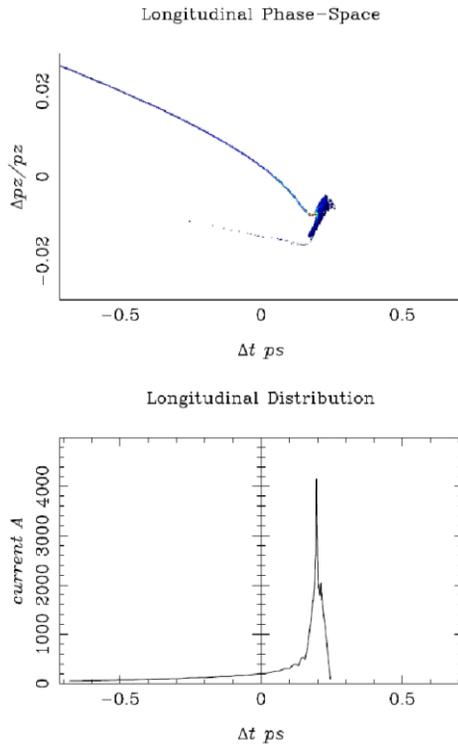
Figure 6: Bunch long. phase space (upper plot) and slices beam current (lower plot) at the end of the linac optimized by the VB technique.

The log. phase space obtained by using the VB, as well reported in Fig. 6, shows a long tail and a very high bunch density on the head, which is its typical charge distribution. The bunch head shows a space charge dominated shape that reshapes the head distribution but the final effect is not under control. The VB final performances, considering the bunch spike, are very good: a slice emittance of 2.5 mm-mrad, a slice current of 4 kA and a slice spread of 350 keV. What is new and peculiar in the LB is the capability to work with a much more uniform bunch distribution, which is clearly shown by the current binning of the Fig. 7. Here, differently from the VB, the capability to control the space charge effect to quasi completely compensate the energy spread, result in a very cold bunch, with the following slice performances: slice emittance below 1 mm-mrad, maximum current of 4kA and a really low energy spread of only 20 keV.

RF SYSTEM

The RF power for the system in Fig. 1 will be provided high-power klystrons driven by solid-state modulators. The 1.6 cell S-Band RF photoinjector is fed by about 10MW of RF power.

The C-band and X-band represent the most crucial components in the proposed LB scheme, therefore particular designs will be carried. Such ad-hoc structures will be powered by two different high-power klystrons at 5.712 GHz and 11.424 GHz, respectively.
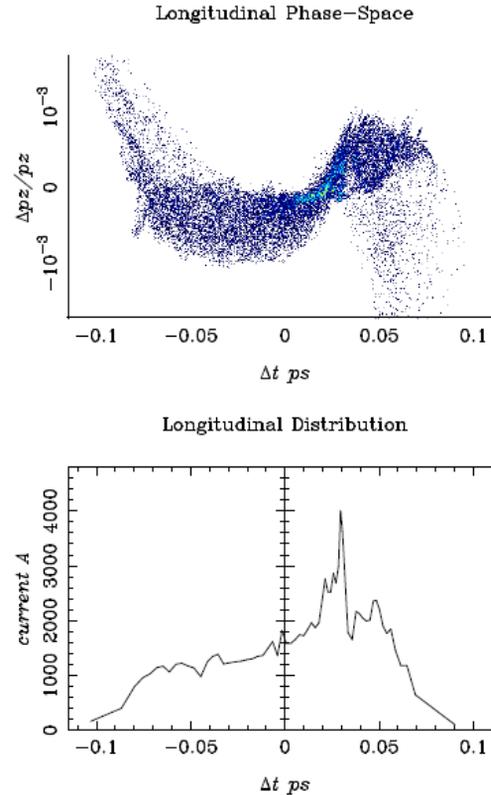
Figure 7: Bunch longitudinal phase space (upper plot) and slices beam current (lower plot) at the end of the linac optimized by the LB technique.

The C-band and X-band devices represent the most crucial components in the proposed LB scheme, therefore particular designs will be carried out. Such ad-hoc structures will be powered by two different high-power klystrons at 5.712 GHz and 11.424 GHz, respectively.

In our simulations, we employed a TW-type *"decelerating"* X-band structure but the standing-wave (SW) option will be also considered, as well as a C-band short cavity, more details are reported into the Ref. [17].

The booster first C-band accelerating structure will be optimized in future studies in order to maximize also the beam focusing. We foresee, for example, the use of cells with modular lengths and fed by separate RF power sources for maximum beam matching.

CONCLUSION

The LB represents another electron beam manipulation method that takes advantage form the space charge nonlinear effects tuning, which is already used for the gun emittance correction; i.e. the great advantage to be able to use non-linear phenomena. The LB performances, as discussed in the paper, are really impressive. It can be considered the only method that besides compressing and preserving the emittance, makes it possible to quasi fully correct the energy spread, opening the horizon to a new type of electron beams: extremely high average current, ultra-cold beams.

REFERENCES

[1] Christopher Kupitz *et al.*, "Serial time-resolved crystallography of photosystem II using a femtosecond X-ray laser", *Nature*, vol. 513, pp. 261–265, Sep. 2014.

[2] T. Tajima, J.M. Dawson, Phy. Rev. Lett., vol. 43, p. 267, 1979.

[3] E. Esarey, Phillip Sprangle, Jonathan Krall, Antonio Ting, *IEEE Transactions on Plasma Science*, vol. 24, 1996.

[4] P. Muggli, Mark J. Hogan, *Comptes Rendus Physique*, vol. 10, p. 116, 2009.

[5] J.B. Rosenzweig, N. Barov, M.C. Thompson, R.B. Yoder, *Phys. Rev. ST Accel. Beams*, vol. 7, p. 061302, 2004.

[6] R. J. Dwayne Miller," Femtosecond Crystallography with Ultrabright Electrons and X-rays: Capturing Chemistry in Action*" Science*, vol. 343, pp. 1108-1116, 2014, doi:10.1126/science.1248488.

[7] E. Chiadroni *et al.*, "Characterization of the THz radiation source at the Frascati linear accelerator", *Review of Scientific Instruments*, vol. 84, p. 022703, 2013, doi.org/10.1063/1.4790429

[8] B. Zeitler, K. Floettmann, and F. Grüner, "Linearization of the longitudinal phase space without higher harmonic field", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 120102, 2015.

[9] k. Floettmann, "Generation of sub-fs electron beams at few-MeV energies", *Nucl. Instr. Meth.*, vol. 740, pp. 34-38, 2014.

[10] C. R. Prokop, P. Piot, B. E. Carlsten, and M. Church, "Beam dynamics performances and applications of a low-energy electron-beam magnetic bunch compressor", *Nucl. Instr.-Meth., Sect. A*, vol. 719, pp. 17-28, 2013.

[11] M. Ferrario *et al.*, "Experimental Demonstration of Emittance Compensation with Velocity Bunching", *Phy. Rev. Lett.*, vol. 104, p. 054801, 2010.

[12] A. Giribono *et al.*, "EuPRAXIA@SPARC_LAB: The high-brightness RF photo-injector layout proposal", *Nucl. Instr. Meth., A*, in press. https://doi.org/10.1016/j.nima.2018.03.009

[13] M. Ferrario *et al.*, "Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the Sparc High-Brightness Photoinjector", *Phy. Rev. Lett.,* vol. 99, p. 234801, 2007.

[14] A. Bacci *et al.*, "GIOTTO: A Genetic Code for Demanding Beam-dynamics Optimizations", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 3073-3076, doi:10.18429/JACoW-IPAC2016-WEPOY03

[15] A.Bacci *et al.*, "Wide-Ranging Genetic Research of Matching Line Design for Plasma Accelerated Beams with Giotto", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, BC, Canada, May 2018, pp. 3561-3564, doi:10.18429/JACoW-IPAC2018-THPAK136

[16] K. Floettmann, ASTRA—A space charge tracking algorithm, http://www.desy.de/~mpyflo/.

[17] D. Alesini *et al.*, "Study of A C-Band Harmonic RF System to Optimize the RF Bunch Compression Process of the Sparc Beam", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 1552-1555, doi:10.18429/JACoW-IPAC2015-TUPW058