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COMPRESSION OF TRAIN OF BUNCHES WITH RAMPED INTENSITY PROFILE AT SPARC_LAB

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Abstract

The production and acceleration of train of bunches with variable spacing in the ps/sub-ps range having ramped intensity profile are interesting to drive a plasma wave in the so-called resonant Plasma Wake-Fields Acceleration (r-PWFA) [1]. At *SPARC_LAB* trains having a constant intensity profile have been produced for the first time by using a shaped photo-cathode laser combined with the use of the velocity bunching compression technique [2–4]. If the sub-bunches have ramped intensity, i.e. they have different charge density, the space charge force affects differently the development of the longitudinal phase space of each one of them during the compression. In this paper we present preliminary simulations for the compression of a ramped train of bunches. The differences between the beam dynamics for a train of bunches having constant intensity profile and the ramped train are underlined. We discuss also the possibility of properly tuning the shaping of the photocathode laser to balance the space charge effect.

INTRODUCTION

Research and Development in the field of Plasma Wakefield Acceleration (PWFA) [5] spread worldwide in the last decades because of the promising results obtained by pioneering experiments such as Ref. [6, 7]. This technique foresees the generation of extremely high (~ GV/m) accelerating gradients having extremely short period (ps or sub-ps) thanks to the creation of a plasma wave in a gas excited by a laser pulse (Laser driven plasma Wake-Field Acceleration - LWFA) or by a particle beam (beam driven Plasma Wake-Field Acceleration).

The use of a train of bunches allows to overcome the main disadvantage of the beam driven acceleration with respect to the laser driven one, i.e. the necessity of a relatively big linac that accelerates the electrons driving the plasma wake-field. Indeed the accelerating field driven by the electron bunch can be increased by resonantly driving the wave through a modulation of the current of the driver.

The transformer ratio of the process is defined as the ratio of the maximum voltage that can be gained by a trailing particle to the voltage lost by a particle in the drive bunch. It can be maximized by using ramped bunch trains as a driver [8].

Nevertheless the beam dynamics of trains of pulses is extremely delicate and the tuning of one parameter (sub-bunch length, sub-bunch transverse emittance, relative spacing) at the entrance of the plasma chamber requires a re-adjustment of the train starting from the photo-cathode.

In this paper we show how it is possible to match a ramped comb driver beam at the exit of the linac by properly shaping the transverse spot size of the different sub-bunches. This method appears to be easy to implement in a realistic experimental setup.

SIMULATIONS

SPARC_LAB Layout

In Fig. 1 the layout of the *SPARC_LAB* facility is shown. The linear accelerator is constituted by a Sband RF gun of the SLAC/UCLA type followed by 3 Sband travelling wave cavities. At the end of the linac is foreseen to be placed a plasma chamber for a beam driven plasma experiment. After the gun there is a short space available for the installation of a linearizing cavity. This element is crucial for obtaining a periodic train spacing after the RF compression. In the following we will include an Xband linearizer located at this position.

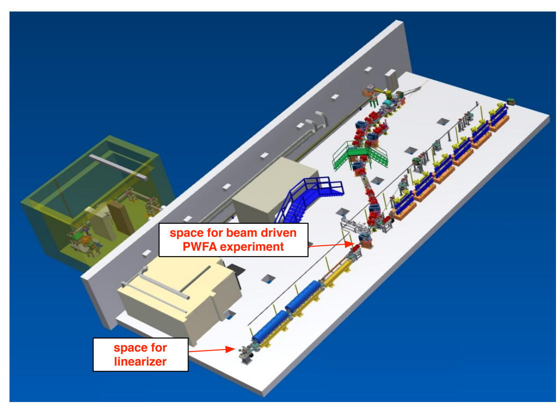

Figure 1: Layout of *SPARC_LAB*.

Compression of a Train of Bunches with Velocity Bunching

At *SPARC_LAB* train of bunches are realized by illuminating the photo-cathode with a longitudinally modulated laser [9–11] , the so-called comb pulse. In this configuration the electrons of each sub-bunch experience a large longitudinal space charge field with a linear correlation along the sub-bunch. The work done by the space charge force produces an energy modulation within the sub-bunch that can be transformed into a density modulation by an RF compressor.

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The compression of the comb beam has a very interesting dynamics: two compressions take indeed place in parallel. First of all there is the compression of the train, that is used to tune the space within the sub-bunches and it is mainly regulated by the phases and amplitudes of the RF cavities. Secondly we observe the compression of each single sub-bunch, which is strongly affected by the photo-cathode laser spot-size and the transverse focusing of the beam.

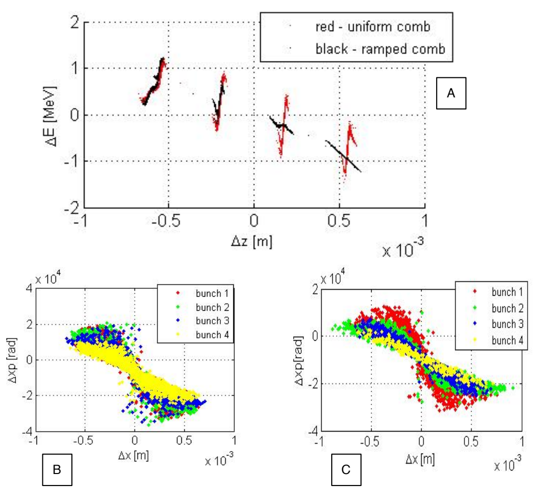

Figure 2: A: longitudinal phase space at the exit of the linac. B: transverse horizontal phase space of the uniform comb beam at the exit of the linac. C: transverse horizontal phase space of the ramped comb beam at the exit of the linac.

When an electron bunch is compressed via velocity bunching transverse and longitudinal dynamics couple via the space charge effect [12]. In particular if the bunch is transversely focused too early in the RF compressor, since it is not yet fully relativistic, the space charge force defocus the beam longitudinally.

Figure 2a shows the comparison of the longitudinal phase space of a uniform train of bunches (i.e. all the sub-bunches have the same charge: 86 pC) and a ramped train (charges of the sub-bunches: 14 pC, 38 pC, 62 pC, 86 pC). The last sub-bunch on the left side is identical in the two cases. In the ramped train, because of the different charge densities, the two sub-bunches on the right side of Fig. 2a are over focused in the RF compressor and because of the space charge repulsion they have longer bunch duration at the exit of the linac. Figures 2b and 2c show the transverse horizontal phase space at the exit of the linac for the uniform and ramped comb respectively. In the first case the ellipses of the 4 bunches are perfectly aligned, while the ramped train presents mismatched phase space ellipses. It would be difficult to better match the beam by simply changing the current of the solenoids, we want to show that it is instead very simple to match them by tuning the laser spot-size at the cathode. This procedure could be easily realized experimentally by placing different irises along the path of the laser sub-pulses before the illumination of the photo-cathode.

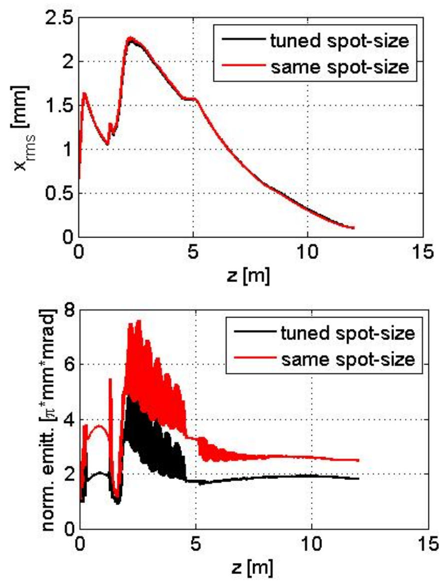

Figure 3: Comparison between the dynamics of the ramped comb having sub-bunches with the same spot-size at the cathode and the ramped comb having tuned spot-size at the cathode. Top: evolution of the train spot-size along the linac. Bottom: Evolution of the normalized emittance of the train along the linac.

Tuning of the Spot-Size along a Ramped Train

All the simulations in this paper have been done by using the code ASTRA [13]. We decided to start from an optimize setup for the uniform comb beam represented in Fig. 2, having total transverse spot-size on the cathode x/yRMS=0.565 mm.

As a preliminary additional optimization, we proceeded as follows:

- we scaled the spot-size of the low charge bunches with respect to the first one (with charge 86 pC), being our reference;
- we re-scaled the spot-size of the entire train on the cathode in order to keep x/yRMS fixed to the starting value;
- we looked at the transverse phase space ellipses of the sub-bunches at the linac exit and iterate the procedure to maximize their superposition.

As a first guess, we would expect to need to reduce the spot-size for the lower charge bunches in order to have the same charge density of the reference bunch, i.e.:

$$R_i = \sqrt{Q_i/Q_{ref}} * R_{ref}. \tag{1}$$

However, since the bunches do not have the same longitudinal to transverse size aspect ratio, and since the dynamics of transverse and longitudinal planes are coupled, this formula over-estimates the change in the spot-size that we need to provide in order to minimize the total emittance of the beam.

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The results of our preliminary optimization are shown in Table 1. Figure 3 shows the evolution of the spot-size and the emittance of the new tuned ramped train with respect to the not-tuned one. Thanks to the laser spot-size tuning along the train, its total transverse emittance at the linac exit decreased by about 30% and the final spot-size has also slightly improved.

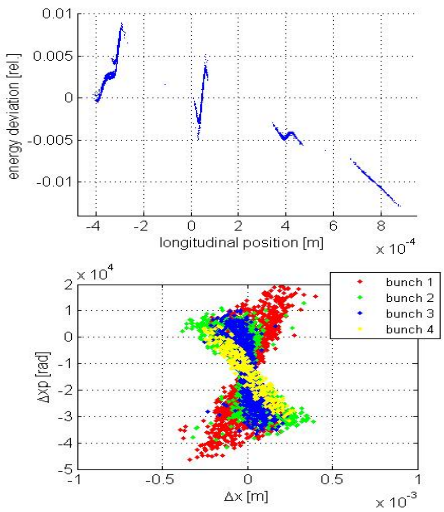

Figure 4: Top:longitudinal phase space at the linac exit corresponding to the non-tuned ramped comb. Bottom:transverse horizontal phase space at the linac exit corresponding to the non-tuned ramped comb.

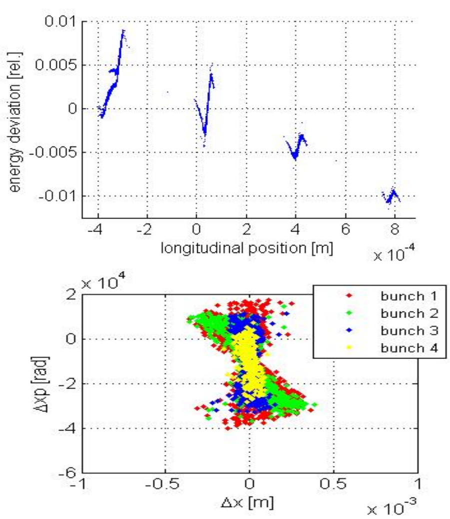

Figure 5: Top:longitudinal phase space at the linac exit corresponding to the tuned ramped comb. Bottom:transverse horizontal phase space at the linac exit corresponding to the tuned ramped comb.

Figures 4 and 5 show longitudinal and transverse (only horizontal) phase space of the ramped train without and with the transverse laser tuning respectively. In the tuned case not only the transverse ellipses of the four sub-bunches overlap better, thus providing a smaller value of the projected emittance of the train, but also the longitudinal compression of the low charge bunches has visibly improved.

Table 1: Laser Transverse Spot-size at the Cathode and Beam Quality Parameters at the Linac Exit

Parameter	**Non-tuned train**	**Tuned train**
Laser x/yRMS b1	0.565 mm	0.643 mm
Laser x/yRMS b2	0.565 mm	0.580 mm
Laser x/yRMS b3	0.565 mm	0.502 mm
Laser x/yRMS b4	0.565 mm	0.363 mm
Electrons $n\epsilon_{x,y}$	2.5 mm*mrad	1.8 mm*mrad
Electrons x/yRMS	99 µm	92 µm
Electrons tRMS b1	100 fs	81 fs
Electrons tRMS b2	36 fs	42 fs
Electrons tRMS b3	86 fs	56 fs
Electrons tRMS b4	153 fs	60 fs
El. bunches rel. distance	1.2 fs	1.2 ps

CONCLUSIONS

We have shown that it is possible to tune the relative orientation of the transverse phase space ellipses of the sub-bunches within a ramped train of bunches by adjusting different irises at the photo-cathode laser. This very simple procedure allowed to decrease the transverse emittance of the train by 30% at the linac exit, to get shorter lengths of the sub-bunches and to slightly improve the final total spot-size of the train.

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