ADVANCED BEAM MANIPULATION TECHNIQUES AT SPARC

A. Mostacci [*,1,2], D. Alesini[2], P. Antici[2], A. Bacci[2], M. Bellaveglia[2], R. Boni[2], M. Castellano[2], E. Chiadroni[2], A. Cianchi[2,3], G. Di Pirro[2], A. Drago[2], M. Ferrario[2], A. Gallo[2], G. Gatti[2], A. Ghigo[2], B. Marchetti[5], M. Migliorati[1,2], E. Pace[2], L. Palumbo[1,2], V. Petrillo[4], C. Ronsivalle[6], A. R. Rossi[2], L. Serafini[4], B. Spataro[2], C. Vaccarezza[2]

[1]Sapienza University, Roma, Italy [2]INFN-LNF, Italy [3]Tor Vergata University, Roma, Italy [4]INFN-Mi, Italy [5]INFN-Roma II, Italy [6]ENEA-Frascati, Italy

Abstract

SPARC in Frascati is a high brightness photo-injector used to drive Free Electron Laser experiments and explore advanced beam manipulation techniques. The R&D effort made for the optimization of the beam parameters will be presented here, together with the major experimental results achieved. In particular, we will focus on the generation of sub-picosecond, high brightness electron bunch trains via velocity bunching technique (the so called comb beam). Such bunch trains can be used to drive tunable and narrow band THz sources, FELs and plasma wake field accelerators.

COMB BEAMS AT SPARC

In this paper we discuss very recent results on beam generation and manipulation of THz spaced electron bunch trains. The technique that we are proposing relies on low energy RF compression (the velocity bunching) and on the use of properly shaped trains of UV laser pulses hitting the cathode of the RF gun (comb laser beam).

Details on the velocity bunching technique and how it is implemented at SPARC can be found in Ref. [1] and related references, as well as a complete SPARC linac description. A comb laser beam is characterized by two or more short (hundreds of fs) pulses spaced by a few ps; it can be generated with a birefringent crystal (e.g. α-BBO in use at SPARC), where the input pulse is decomposed in two orthogonally polarized pulses with a time separation proportional to the crystal length; adding more birefringent glasses one can generate multi-peaks light beams [2].

A comb laser pulse illuminating a photocathode in a RF gun can generate a train of short electron bunches. Downstream the gun, the beam acquires an energy modulation because of the space charge effects and, if injected in a RF-compressor or in a magnetic chicane with negative R_{56}, the energy modulation can be transformed back into a density modulation [3]. Previous experimental results with two bunches after a RF compressor at SPARC are reported in Ref.s [2, 4]; the total bunch charge was ranging from 70 to 180pC and the energy was varying from 164 to 110MeV, depending on the injection phase in the bunch compressor. Coherent THz radiation was produced with such 180pC beam with the two sub-bunches separated of 0.7ps [5].

Several groups are performing R&D on the generation and manipulation of such bunch trains. For example, a birefringent crystal to shape the laser pulse is adopted also by L. Yan *et al*. at Tsinghua University [6]; they are using four pieces of α-BBO crystals to separate an input UV pulse with appropriate duration into 16 sub-pulses to form a ps-spaced pulse train suitable for coherent THz emission. Production of ps-spaced bunch trains with up to four bunches at 2.8MeV beam energy and with a total beam charge of 40–50pC has been demonstrated with this scheme [7].

A completely different approach to produce THz repetition rate bunch trains is placing a mask in a high dispersion, low beta function region of a beam line dogleg in order to produce a temporal bunch train out of a long bunch with a correlated energy spread. A train of 6-7 bunches with a charge not greater of 20pC in the most charged sub-bunch has been experimentally achieved at 58MeV (see [8] and related references).

A THz repetition rate bunch train can also be generated with a transversely segmented beam (with a multislit mask) via a transverse-to-longitudinal phase space exchange technique, obtained placing a deflecting cavity between two dispersive sections. Such a scheme has been used to generate 14MeV, five bunches train with total charge of 15pC and applied to enhance narrow-band THz radiation emission from a transition radiation screen [9].

The so called "comb scheme" (comb laser pulse and RF compression) presently under development at SPARC has two main peculiarities with respect to other schemes discussed above: the production of the bunch train does not rely on beam losses (and therefore it can accommodate naturally higher charge in the bunches) and the final bunch train parameters can be tuned only varying the accelerator working conditions. Both properties are interesting for several applications, such as Plasma Wake Field Acceleration (PWFA) or resonant enhancement of the THz radiation production or ultra-fast pump and probe experiments with FEL photons. Moreover the comb scheme offers the possibility of tailoring the bunch train shape, as needed for example in PWFA.

In this paper we report on the manipulation of two/four sub-bunches train at charge higher than demonstrated so far with other schemes, while their use for THz radiation generation is discussed in Ref.s [10, 11] and for FEL radiation

* Andrea.Mostacci@uniroma1.it

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pulses generation in [12]. Before entering in the experiment details, we shall highlight the main physical aspects of the comb beam dynamics, starting from the simpler case of a two sub-bunches train and focusing on the accelerator parameters mostly affecting the beam behavior.

General issues on comb beam manipulation

Figure 1 shows the compression curve for a two bunches train from a TSTEP simulation [13] with parameters relevant for the SPARC linac. A 165pC, two sub-bunches (each of 145fs rms beam size) train is extracted from the cathode with a bunch distance of 4.27ps and equally distributed charge; the RF gun boosts its energy up to 4.7MeV and then the train enters the first TW section (1.5 meter after the cathode) at different injection phases. The compression phase of Fig. 1 refers to the difference from the injection phase and the "on crest" (maximum energy at the linac exit) phase. The compression factor is the ratio between the on crest bunch length and the actual bunch length (which varies with the compression phase). The final energy of the beam depends on the compression phase and ranges from 177MeV (on crest situation) to roughly 100MeV in over-compression (i.e. for compression phases more negative than the maximum compression one).

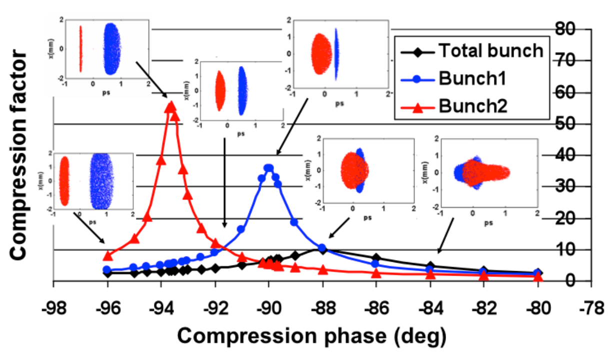

Figure 1: Compression curve for two bunches pulse train at SPARC (simulation, total charge 165pC).

Figure 1 describes the longitudinal behavior of the whole bunch and of each sub-bunch (blue data refers to the bunch first hitting the cathode, red data to the other). The black (blue, red) line is the compression factor for the total (first, second) bunch at different phases. The total bunch length decreases up to a minimum value (-88 deg) and, up to that moment, the two bunches are in the same relative position as at the gun cathode. Increasing the compression phase, the sub-bunches invert their relative position and they start to become distinguishable and to increase their separation. Anyway, the dynamics of each sub-bunch is different: the first bunch reaches its minimum length (max compression, 200fs rms length) while the second is still in a moderate compression regime (red, blue line of Fig. 1). If some application needs the same current in the two bunches, the working point is close to the interception of the two curve (not exactly at the interception because the bunch shape is different in compression or over-compression [14]). In this simulation, the bunches are well separated at compression phases smaller than -90deg and the sub-bunch distance (not shown) depends more or less linearly with the compression phase in this region. An interesting range for the applications, i.e. 0.6–1.1ps bunch spacing is obtained between -91 and -94deg in this simulation.

It is clear that to have good separation, one has to operate in over-compression regime, which implies a careful machine optimization to preserve significantly low emittances. On top of that, the experimental reconstruction of the sub-bunches dynamics is not trivial, since the bunch length measurement resolution needed to precisely resolve the sub-bunches is demanding.

As a general rule of thumb, the bunch separation is roughly twice the total bunch length in over-compression and such separation is completely frozen at the end of the first 3m TW section (the SPARC RF compressor). For a given compression phase, the sub-bunches separation increases for increasing the laser pulses distance on the cathode and the whole bunch charge (i.e. the space charge contribution).

The phase distance of the maxima of the sub-bunches compression curves (that is of the sub-bunches minimum length) depends mainly on the pulse distance at the entrance of the RF compressor which, for a given RF gun injection phase, is determined by the space charge: the pulse distance at the RF compressor entrance increases with bunch charge and moving the gun injection phase towards the phase of maximum charge extraction. Simulations show that such a phase separation of the maxima can be inferred from the pulse distance of the on crest beam at the linac end. The sub-bunches minimum length (and thus their maximum compression) is in general different, being identical only in the ideal case of no space charge beams injected with the same energy in the compressor.

The SPARC linac is composed by three 3m TW sections after the gun (the first one being the compressor) and the beam injection phase can be varied autonomously for each section; usually the second and the third section are phased to get the maximum energy at the linac exit. By changing the last section phase (i.e. the whole beam energy), only the energy (and not the time) separation is affected; in particular there is no effect on the sub-bunches current distribution.

The difference between the sub-bunches charges at the cathode does not affect the separation at the linac exit (for a given compression phase), while it affects the sub-bunches currents and bunch lengths.

Emittance compensation during the RF compression requires focusing additional to the acceleration one, which in the SPARC case is provided by two 3m (independently powered) solenoids embedding the first two TW sections. Typically only the solenoid around the first accelerating section is used at operation values in the range of 270-330G (for all the data/simulation presented here). Such mag-

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netic field has a negligible effect on the separation, while it affects the emittance (at the linac exit), the sub-bunches bunch length and current (but not the sub-bunches current ratio) and the compression phases corresponding to the single bunch compression curves maxima, which are (more or less) rigidly shifted by varying the magnetic focusing field.

As usual in RF gun based linac, the main knob to control the emittance is the solenoid embedding the gun, affecting the emittance of the whole bunch as well as of the sub-bunches, together with their length and currents. The minimum emittance of the whole bunch, the minimum emittance of each single sub-bunch and an equal current in the sub-bunches occur at different values of the gun solenoid field; typically for the SPARC case, these values differ no more than roughly 300G.

As a rule of thumb, the minimum emittance of the whole bunch, the equal current and the minimum spot size at the linac exit occur for close values of the gun solenoid field. On top of that, simulations suggest that the minimum emittance of the whole bunch occurs when the two sub-bunches are radially separated at the linac exit, i.e. one forms a ring around the other in the transverse spot. During machine operation, this condition can be often observed (especially for "well behaved" beams) by letting the beam propagating for roughly 5 meters after the linac without additional (quadrupole) focusing. Therefore such situation was used as starting point for emittance optimization in the experiments discussed below.

All those guidelines were followed during the experiments performed recently with two bunches (200–400pC) and four bunches (200pC) train; the train average energy at the linac exit was varying from 170 to 90MeV, depending on the machine setting, mainly the compression phase (used to tune the sub-bunches distance) and the last section phase (used to tune the sub-bunches energy separation).

The use of the RF compressor in the over-compression regime requires good beam quality (i.e transverse emittance) and overall machine stability. A poor beam emittance would spoil the brilliance and/or would imply a too large beam to be manipulated; the compression phase stability is important to keep the separation in the comb beam constant during operation. The first goal was achieved with the increase of beam energy at the gun exit (best value being 6.2MeV) by shaping the RF pulse to reduce the breakdown rate [15], while the compression stability largely profited of a dedicated chilling of the first TW section of utmost importance in the RF compression.

The goal of most of the experiments was enhancing THz radiation by use of ps-spaced, hundreds of fs long sub-bunches [5, 10]; therefore most of our effort was oriented to obtain a stable longitudinal configuration with tunable bunch spacing. The transverse emittance optimization was addressed only to obtain a loss free transport in the dogleg line where the THz station was located.

TWO BUNCHES TRAIN

A first experiment was performed with two comb pulses (145fs FWHM each with a separation of 4.27ps), extracting a beam of 160pC (total charge). The gun exit energy was 4.51MeV and the gun injection phase is 23deg from the gun phase scan zero crossing (30deg corresponds to maximum gun exit energy) [16]. Such a choice was an attempt of reducing the sub-bunches spacing at the RF compressor entrance. The beam on crest was 1.880 (0.041)ps long with an energy of 177MeV and energy spread <0.1%. Figure 2 shows the bunch length as a function of the compression phase. Decreasing the compression phase, the beam energy decreased up to roughly 110MeV and the energy spread increased up to roughly 0.7%; the charge in the pulses was unbalanced (63% - 37%). The agreement with TSTEP simulation is satisfactory.

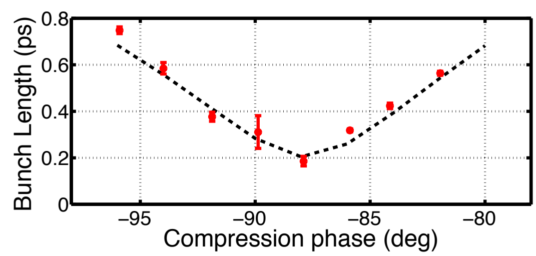

Figure 2: Measured compression curve for a two bunches train compared to TSTEP simulation (total charge 160pC).

The separation between the pulses approached the target value of 1ps in the over-compression regime (see Fig. 3, -96 ÷ -94deg region) where the two sub-bunches were clearly separated. For bigger (i.e. less negative) compression phases, the longitudinal profile was only modulated, but the bunches not actually well separated. Typically bunch length and sub-bunches separation measurement are quite reproducible and easily in agreement with start-to-end simulation, while emittance measurement require more attention and emittance optimization is not always trivial. For example, the vertical emittance was optimized for the -96deg of compression phase with a gun solenoid scan reaching ε_y=3.03 (0.12) mm-mrad while the horizontal measurement was spoiled by chromatic effects, probably due to a large spot size at the quadrupole entrance and the energy spread of the over-compressed beam.

A gun exit energy greater than 5.6MeV allowed us to successfully manipulate higher charge, two pulses beams. An example is shown in Fig. 4 where the Longitudinal Phase Space (LPS) of a 300pC beam is reported for different compression phase. The on crest case is in Fig. 4.a; injecting out of phase in the first TW section, the phase space rotates counter clockwise entering in the compression regime (Fig. 4.b) up to when it reaches the minimum length (Fig. 4.c, maximum compression). Decreasing the compression phase, the LPS continues rotating entering the over-compression region, where sub-bunches are longitu-

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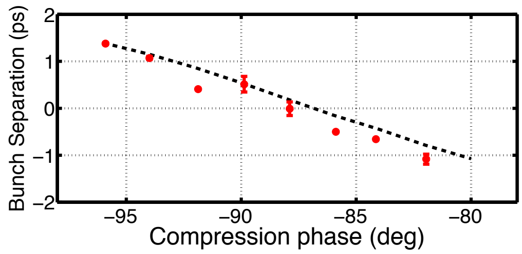

Figure 3: Measured bunch separation for a two bunches train compared to TSTEP simulation (total charge 160 pC).

dinally separated and their separation can be tuned by adjusting the compressor phase (Fig. 4.d). The gun extraction phase is set to 35deg (from the phase scan zero crossing) and therefore the two bunches are entering the compressor at a larger distance than in the previous case (due to higher the gun extraction phase and bigger space charge).

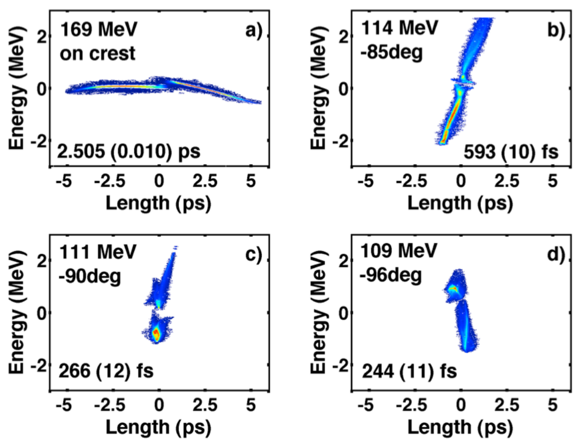

Figure 4: Measured LPS for a two pulses comb beam; the label reports the average energy, the compression phase and the rms bunch length (150 pC in each sub-bunch).

Concerning the emittance optimization, the use of the solenoid around the compressor was unavoidable in the (over) compression regime while its effect is negligible for the on crest situation (as predicted by the simulation). The whole bunch emittance was optimized by tuning the gun solenoid field and single sub-bunch emittance optimization was not performed, since it is not necessary for THz radiation generation experiment [10]. As an example for the 300pC case, the focusing magnetic field at the gun used for the emittance optimization was in the range of 2.8-2.9 10^3G for the (over) compression points, while roughly 3.0 10^3G for the on crest condition. The focusing field in the first TW section was in the 270G range. Table 1 shows the achieved projected emittances (with their uncertainties) for different bunch charges and for a 90% cut [17]. The high value measured in the (over-) compression regime can be partially explained with measurement

Table 1: 90% transverse emittance $\sqrt{\varepsilon_x \varepsilon_y}$ in mm-mrad

	180pC	**300pC**	**400pC**
on crest	0.539 (0.024)	0.858 (0.024)	1.382 (0.055)
comp.	1.904 (0.037)	1.59 (0.11)	2.170 (0.074)
max comp.	2.92 (0.18)	3.19 (0.76)	5.28 (0.66)
over comp.	4.22 (0.21)	6.6 (1.0)	14.2 (1.2)

artifacts due to the different evolution of the sub-bunches during the quadrupole scan, clearly seen in operation especially for mismatched beams.

All three charge points have been fully characterized, in term of longitudinal (i.e. bunch length, separation, energy spread and longitudinal emittance) and transverse (i.e. emittance) properties; the longitudinal analysis has been performed both on the whole bunch as well as on each sub-bunch. The data are in excellent agreement with start to end simulation with TSTEP.

FOUR BUNCHES TRAIN

The LPS evolution of a four bunch train in the RF compressor is shown in Fig. 5: increasing the compression phase, the beam LPS rotates counter clockwise from the maximum linac exit energy (Fig. 5.a), to the compression regime (Fig. 5.b), then to maximum compression (Fig. 5.c) thus entering the over-compression (Fig. 5.d-f), very similarly to the two bunch case discussed above in Fig. 4.

The relevant regime for the application, i.e. where the sub-bunches are well separated and their distance can be tuned with the RF compressor injection phase, is after the phase when the minimum energy spread is reached (Fig. 5.e) namely the "deep" over-compression (e.g. Fig. 5.f).

We have carefully investigated this regime, both numerically and experimentally. As an example, Fig. 6 shows another case of deep over-compression compared to TSTEP simulation, showing excellent agreement. The simulated LPSs are always thinner than the measured ones possibly due to RF deflector measurement issues (resolution and/or non-zero transverse emittance). One can see that the first two sub-bunches (on the left side of the picture) have a negative energy chirp while the other two have it much closer to zero. The first two sub-bunches of Fig. 6 correspond to the ones entering later in the RF compressor (red particles in Fig. 1). The energy chirp of the whole bunch and the sub-bunches energy separation can be tuned adjusting the beam entrance phase in the third accelerating section (while the sub-bunches current and spacing remain unchanged); the sub-bunches energy chirp is affected as well, but in a much smaller way.

As for the two bunches case, the longitudinal behavior of the whole bunches, as well as, of each sub-bunch has been analyzed deeply while only the whole bunch trans-

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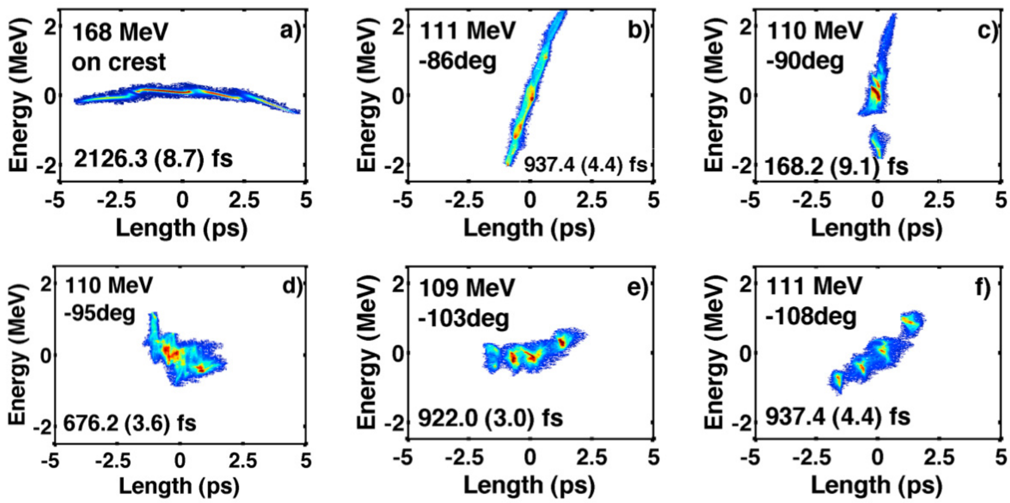

Figure 5: Four comb pulse longitudinal phase space rotation; the label reports the average energy, the compression phase and the rms bunch length (200pC).

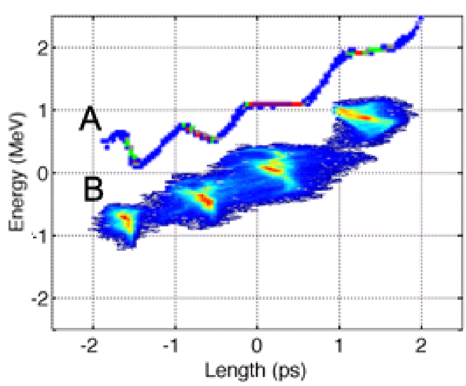

Figure 6: Comparison of measured longitudinal phase space (B) to simulated one (A). (200 pC)

verse emittance has been exhaustively studied. As predicted from simulation, the transverse emittance is less sensitive to the gun focusing field in the four sub-bunches case than with two sub-bunches; again the solenoid embedding the RF compressor was of primary importance. As a matter of fact, in deep over compression regime the horizontal emittance optimization (and measurement as well) was far more difficult than the vertical one. Table 2 reports typical values of $\sqrt{\varepsilon_x \varepsilon_y}$ (first three lines) and ε_y (last three lines) concerning the measurements shown in Fig.5-6.

Table 2: 90% transverse emittance (mm-mrad), 200 pC.

on crest	1.114 (0.026)	see Fig.5.a
comp.	1.802 (0.047)	see Fig.5.b
max comp.	4.01 (0.11)	see Fig.5.c
over comp.	3.78 (0.17)	see Fig.5.e
deep over comp.	4.49 (0.16)	see Fig.5.f
deep over comp.	4.09 (0.12)	see Fig.6

CONCLUSIONS

The comb scheme (comb laser pulse and RF compression) proposed in 2007 [3] is an active method to generate THz repetition rate bunch trains without the introduction of beam losses. We have demonstrated experimentally the control of pulse spacing, length, current and energy separation by properly setting the accelerator. In this paper we have reported on the manipulation of two/four sub-bunches train with a charge ranging from 200 pC to 400 pC at energies greater than 100 MeV.

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