

# CHARACTERIZATION OF PS-SPACED COMB BEAMS AT SPARC

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## Abstract

SPARC in Frascati is a high brightness photo-injector used to explore advanced beam manipulation techniques. Sub-picosecond, high brightness electron bunch trains (the so called comb beam) can be generated illuminating the cathode of a RF photoinjector with a laser pulse train and via velocity bunching technique. In this paper different aspects of the physics of this advanced beam manipulation technique are discussed combining simulation and measurements. Beam dynamics numerical macroparticle simulations have been compared with the experimental results for model validation; they allow to gain insights on the beam evolution highlighting several aspects which can not be measured. In particular, we focus on the train evolution in the linac sections and in the dogleg line up to the THz station and on the effective rms length of the single pulses within the train when it becomes shorter than the resolution.

## INTRODUCTION

The production of a pulse train with sub-picosecond length and adjustable (sub)-picosecond inter-distance is very interesting due to its wide spectrum of applications such as coherent excitation of plasma waves in plasma accelerators, ultrafast pump-probe FEL experiments and generation of narrow-band THz radiation.

The technique consists in illuminating, with a comb laser pulse, a photocathode in a RF gun followed by a RF compressor operating in over-compression regime or by a magnetic compressor with  $R_{56} < 0$ : downstream the photoinjector the initial density modulation is converted, due to space charge, in energy modulation, that after compression is transformed back in density modulation. The train parameters are completely controlled by the accelerator with no particle losses, giving the possibility to produce high charge pulse trains.

SPARC uses RF compression (velocity bunching) to produce high brightness longitudinally compressed beams [1]. The SPARC linac (Fig. 1) is composed by a BNL/UCLA type gun followed by three TW sections whose accelerating gradient can be changed independently by adjusting the phase entrance. The first one is used as RF compressor by

varying the injection phase of the beam. The THz source is placed at the end of the dogleg line, where a Coherent Transition Radiation (CTR) is generated at the interface of an Aluminum coated Silicon screen. CTR is then extracted and sent to a Martin Puppel interferometer for diagnostics [4, 5].

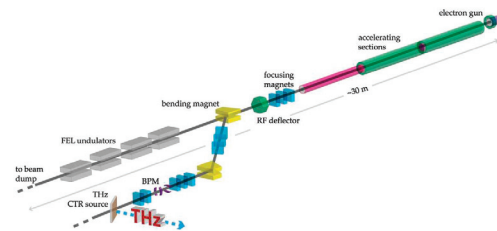


Figure 1: SPARC schematic layout with the THz source placed at the end of the by-pass line.

In recent papers we have shown the details of the experimental set-up [2] with the main results [3]-[6]; we refer to them for a detailed description of the layout.

In this manuscript we discuss some insight in the beam dynamics for a four bunches comb beam and some issues concerning the operation of the THz radiation source.

During the experiment we extensively used start-to-end simulation to guide the operation and to analyze the data. Therefore we can rely on a quite accurate machine model (checked against experiments) which allows us also to investigate interesting features of comb beam which are beyond the resolution of our measurement systems.

## FOUR BUNCHES TRAIN

The compression curve of the whole bunch is shown in Fig. 2; it reports the ratio between the bunch length at the maximum energy (i.e. no compression) with the bunch length for each injection phase in the first TW accelerating section (i.e. the RF compressor phase). Three different working conditions, namely compression, over-compression and deep over-compression, can be identified from the rotation of the phase space induced by the velocity bunching [2]. From the point of view of the applications which need a tunable bunch separation, the over-compression region is the most interesting one. Indeed the

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bunch separation can be modified by simply changing the compression phase [2].

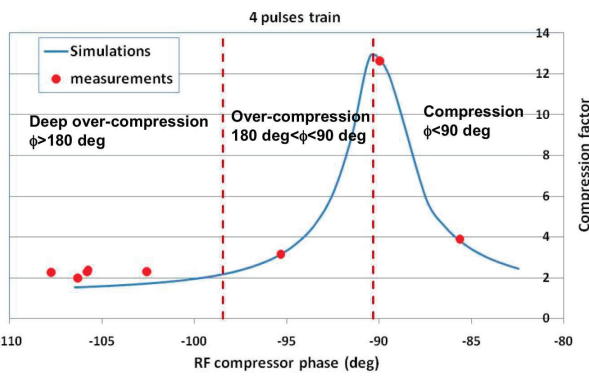


Figure 2: Whole bunch compression curve for the 4 sub-bunches train (TSTEP simulation [7], measurements).

The start-to-end TSTEP simulations are in excellent agreement with the measured data and we can use them to investigate the beam dynamics. For example, Fig. 3 reports the compression curve for each of the four bunches as well as the whole bunch one. The single sub-bunches lengths are too small to be measured directly with our RF deflector.

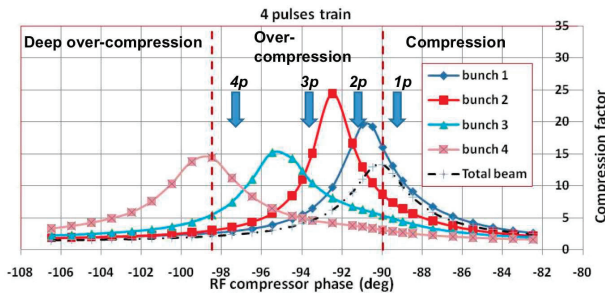


Figure 3: Compression curve of each bunch of the comb beam (TSTEP simulation [7]).

Figure 3 shows also that the RF compressor phases can be used as a selector of the number of pulses in the final train. In the compression region, the bunch current exhibits only a longitudinal modulation. By entering in the over-compression region, as soon as the first (head) sub-bunch is going through its maximum compression (diamond line) and before the maximum compression of the second sub-bunch (red square line), the current appears as two sub-bunches ( $2p$  label). By increasing the RF compressor phase, we can move towards a three sub-bunches train ( $3p$  label) and eventually towards a four sub-bunches train ( $4p$  label).

Another interesting feature which is worthwhile mentioning is the ability of tuning the energy separation of the sub-bunches, as well as the whole bunch energy spread.

Figure 4 shows the longitudinal phase space in the deep

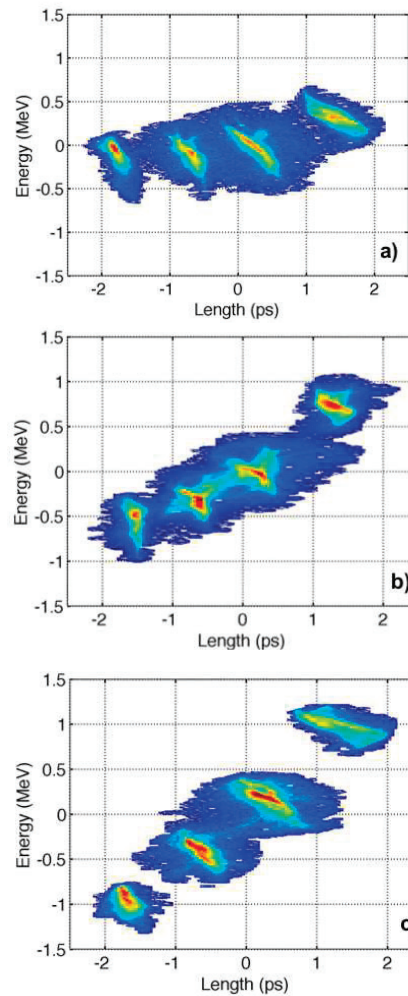


Figure 4: Effect of the last accelerating section of the SPARC linac on the longitudinal phase space (200pC).

over compression region for the same RF compressor phase (see Table 1) but for different accelerating gradients of the last TW section. The rms bunch length and the average time separation are identical within the measurement uncertainties, since they depend mainly on the compression phase. As expected the bunch separation is remarkable and such bunches have been used for THz radiation production [5]. Nevertheless the different accelerating gradient affects the average energy, the energy spread and the average energy separation, as shown in Table 1.

## DOGLEG LONGITUDINAL DYNAMICS

The longitudinal phase space evolution in the dogleg is dominated by non linearities given by high order chromatic terms [8]. Running the beam off-energy with a momentum  $\tilde{p}$  differing from the central momentum  $p_0$  of the design trajectory, the beam centroid follows the trajectory of an off-momentum particle whose momentum dispersion is  $\Delta = (\tilde{p} - p_0)/p_0$ . A particle with arbitrary momentum  $p$  then has the momentum error  $\tilde{\delta} = (p - \tilde{p})/\tilde{p}$  relative to

Table 1: Longitudinal beam properties for different setting of the last accelerating section of the SPARC linac. The time (energy) separation are average values.

	Fig. 4.a	Fig. 4.b	Fig. 4.c
Compression phase (deg)	106.3	105.8	106.3
Bunch rms length (ps)	1.06	0.93	0.97
Time separation (ps)	1.03	0.96	1.00
Energy (MeV)	91.4	111.4	112.5
Energy spread (%)	0.3	0.4	0.6
Energy separation (MeV)	0.13	0.45	0.65

the central momentum of the beam and the momentum error  $\delta = (p - p_0)/p_0$  relative to the design momentum for which the beam line is optimized. The longitudinal transport relative to the displaced momentum error  $\tilde{\delta}$  is

$$z_f = z_0 + \tilde{Q}_5 + \tilde{R}_{56}\tilde{\delta} + \tilde{T}_{566}\tilde{\delta}^2 \text{ where } \tilde{T}_{566} = T_{566}(\tilde{p}/p_0)^2, \\ \tilde{R}_{56} = \frac{\tilde{p}}{p_0}(R_{56} + 2T_{566}\Delta) \text{ and } \tilde{Q}_5 = R_{56}\Delta + T_{566}\Delta^2$$

are function of the momentum error  $\Delta$  from the beam centroid, i.e. the difference between the actual energy and the design one.  $z_0$  is the designed longitudinal position; additional details of the derivation and the notation used here are explained in Ref. [8].

In a comb beam we can define the previous quantities for the whole beam and also for each sub-bunch in the train, meaning that any sub-bunch may undergo a longitudinal evolution different from the others.

For example, typical values for SPARC dogleg line are  $R_{56} = -5\text{mm}$  with a  $T_{566} = -95\text{cm}$  with a momentum spread which may be about few %; therefore the  $\tilde{R}_{56}$  (so called “effective”  $R_{56}$ ) may also change sign within the bunch train itself. In a two sub-bunches beam we have observed (in simulations) one sub-bunch lengthening while the other is compressing, explaining the measured THz spectra.

Such a non linear behavior is very important, since the dogleg acts as a compressor i.e. modifying further the bunch train length, sub-bunches current and bunch separation. An example is shown in Fig. 5 comparing the longitudinal phase space at the exit of the linac (where the SPARC longitudinal beam diagnostics is) and at the end of the dogleg (where the THz radiation source is).

At the linac exit the four pulses are well separated (left plots). The right plots refers to a dogleg line with the quadrupoles set to have  $R_{56} = -5\text{mm}$  with an energy 1MeV lower than the energy at which the dogleg is optimized. The longitudinal phase space is completely distorted and the bunch profile has a modulation depth much worse, resulting in a poor THz emitted radiation. Figure 5 shows TSTEP [7] simulation with a very detailed SPARC model and the resulting THz spectra are compatible with the measured ones.

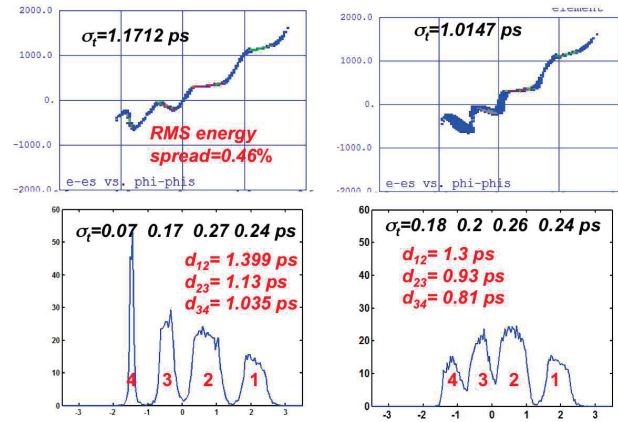


Figure 5: Longitudinal phase space and current profile at the Linac exit (left plots) and at the THz station (right plots) (TSTEP simulation [7]).

Such high order chromatics effect (due to  $T_{566} \gg R_{56}$ ) and possible off energy operation affects the longitudinal phase space transport in the dogleg even more for a two bunches comb beam which exhibits typically a higher energy spread. On the contrary, one can use the last accelerating section to reduce the energy spread along the bunch train, as shown in Fig. 4.

## CONCLUSIONS

The comb scheme (comb laser pulse and RF compression) proposed in 2007 [9] 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 investigated some issues of the longitudinal dynamics in the over-compression regime needed for comb-beam manipulation. Moreover the effect of the dogleg parameters in the THz experiment at SPARC has been highlighted.

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