VELOCITY BUNCHING EXPERIMENTS AT SPARC

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Abstract

During the last SPARC run a preliminary experimental study of the velocity bunching technique has been performed. Bunch length and projected emittance have been measured at the linac exit as a function of the injection phase in the first accelerating structure and for different solenoids field values. A maximum compression ratio up to a factor 13 has been observed. In particular a peak current of 120 A with 300 pC in a 2.3 ps FWHM long bunch with emittance lower than 2 mm-mrad has been measured with a compression factor 3. In this paper we describe the results achieved so far and a comparison with simulations is also reported.

INTRODUCTION

One of the main goals of the SPARC high brightness photoinjector is the experimental demonstration of the emittance compensation process while compressing the beam with the Velocity Bunching technique [1]. For this reason the first two S-band travelling wave accelerating structures, downstream the 1.6 cells S-band RF gun, are embedded in long solenoids, in order to keep under control the space charge induced emittance oscillations when the bunch is compressed.

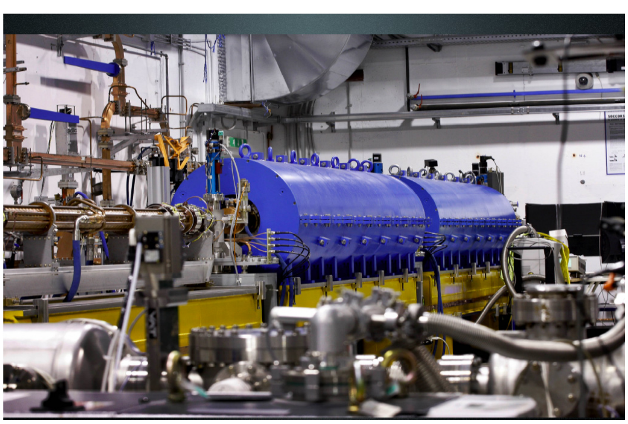

Figure 1: Photo of the SPARC photoinjector showing the 3 accelerating structures with 2 long solenoids

The SPARC beam diagnostic allows rms beam envelope measurements on four YAG screens: three screens are located at the entrance of each RF structure while the fourth one is located at the exit of the linac. On the last screen the rms emittance is measured by a quadrupole scan [6]. A RF deflecting cavity placed at the exit of the third accelerating structure allows bunch length measurements with a resolution of 50 µm. A photo of the SPARC photoinjector is shown in Fig. 1.

During the last SPARC run a preliminary experimental study of the velocity bunching technique has been performed and the main results are reported in the next sections. In the past velocity bunching experiments have been already performed in other laboratories [2,3,4,5]. Since they haven't been done on a machine specifically designed for this kind of process and the final beam brightness has not been fully satisfactory.

VELOCITY BUNCHING CONCEPT

The longitudinal phase space rotation in the Velocity Bunching process is based on a correlated 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 happens inside the longitudinal potential of a traveling RF wave (longitudinal focusing) which accelerates the beam inside a long multi-cell 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 will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed. The key point is that compression and acceleration take place at the same time within the same linac section, actually the first section following the gun, that typically, under these conditions, accelerates the beam from < 5 MeV up to 25-35 MeV.

LONGITUDINAL FOCUSING

The first measurements made at SPARC were devoted to study the compression ratio as a function of the injection phase, without any external focusing (solenoids off). We have been operating with a quasi-Gaussian longitudinal laser profile, shown in Fig. 2, ~7.5 ps FWHM long and with 300 µm of transverse spot size. The bunch charge was 300 pC resulting in an initial peak current around 35 A.

When the beam has been accelerated on crest by an accelerating field of 20 MV/m in the first two sections and 10 MV/m in the last section, the final energy was 150 MeV with an energy spread of 0.1% and an energy stability better than 0.1%. The rms bunch length measured at the linac exit was 3.25 ps.

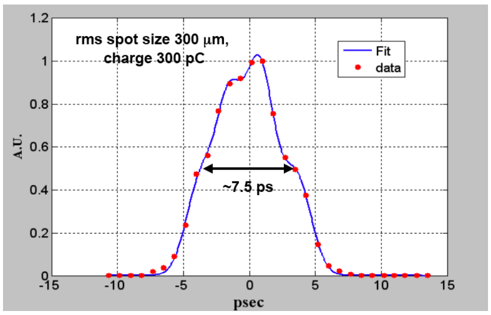

Figure 2: Laser temporal profile.

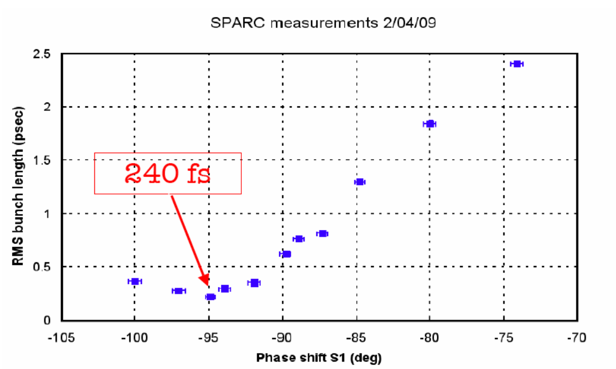

Figure 3: Measured rms bunch length of a 300 pC beam versus the phase of the first travelling wave structure.

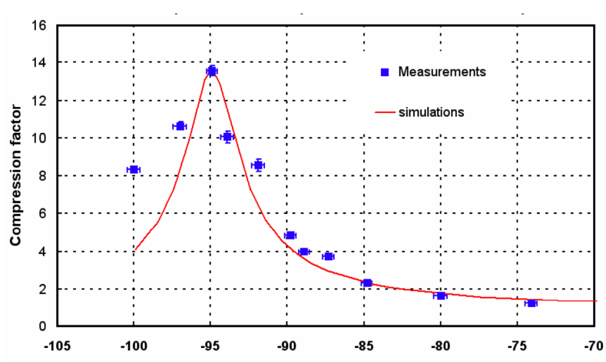

Figure 4: Compression factor versus injection phase, PARMELA simulations are also shown.

Figure 3 shows the measured rms bunch length versus the injection phase in the first travelling wave structure. The error bars have been calculated over the 10 images collected for each measurement, a more detailed study including jitters effects and systematic error will be the subject of future investigations. A significant bunch compression occurs only after a phase shift of 85 degrees, the beam energy was progressively observed reducing to 100 MeV and the energy spread grows up to 1 %. In the next 10 degrees shift (from -85 to -95) the strong compression regime occurs, as expected, with almost the same final energy and energy spread. The shortest rms bunch length we have measured was 240 fs, (72 µm) limited by the longitudinal beam emittance. During this measurements the minimum spot size with the RF deflector turned off was 30 µm. The last two measurements also show the over-compression effect when the phase setting exceeds -95 deg. In Figure 4 the compression ratio versus the injection phase is also shown. The red curve is the results of PARMELA simulation. The agreement is quite satisfactory up to the maximum compression ratio.

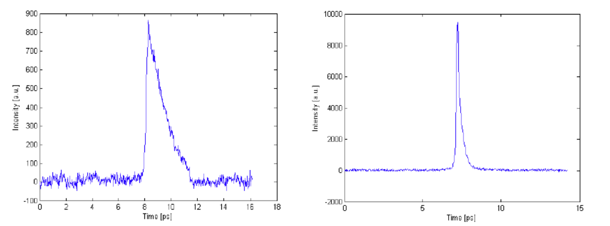

Figure 5: Beam longitudinal profiles as reconstructed by the experiments. Compression ratio 3 (left), compression ratio 13 (right).

The beam profiles as retrieved by measurements are also shown in Fig. 5 for two different compression ratio.

We have measured also the long term stability of the Velocity Bunching operating with a compression factor 3. Figure 6 shows five bunch length measurements performed every five minutes proving a long term stability of about 100 fs.

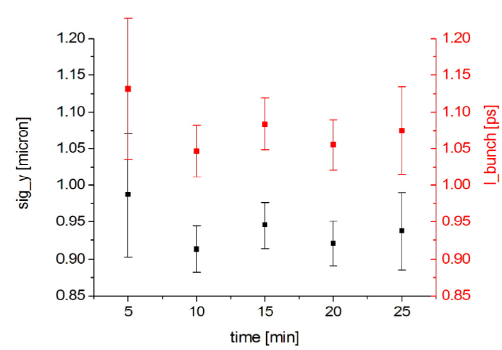

Figure 6: Long term stability with a compression factor 3.

EMITTANCE COMPENSATION

The emittance compensation optimization requires a careful tuning of the solenoid field in order to keep under control the space charge induced emittance oscillations. In addition the beam based alignment of the two long solenoids has not yet been done, thus a lengthy compensation of the transverse kicks the beam receives by the coils is required with the beam trajectory correctors. In this condition a systematic study of the emittance compensation process has been possible only for one case and we concentrated our attention on a moderate compression ratio 3.

In Fig. 7 the measured envelopes are shown in comparison with simulation for three different conditions: no compression (beam on crest), compression with solenoids off, same compression with all solenoids set to 400 Gauss. The corresponding emittances evolution along the linac are shown in Fig. 8. The effectiveness on the emittance compensation produced by the solenoids is clearly visible from the simulation and it is in good agreement with our measurements.

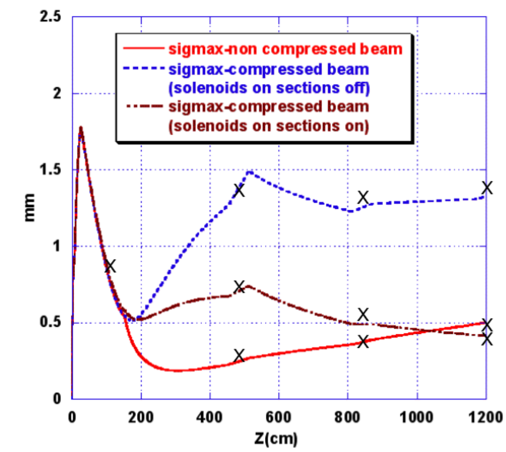

Figure 7: Measured envelopes (x) and PARMELA simulations.

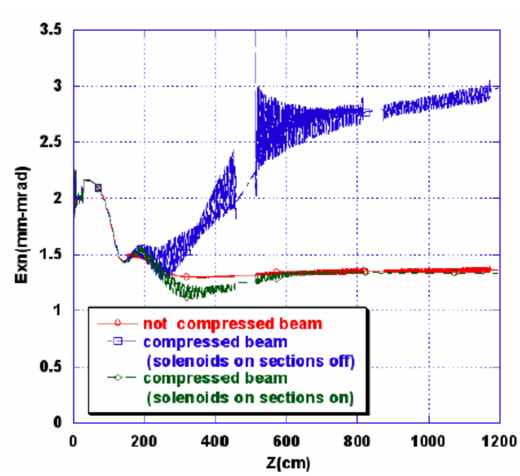

Figure 8: Emittance evolution along the linac, PARMELA simulations.

In Tab. 1 the measured beam parameters are reported. The second column contains the measured data of the uncompressed beam (on crest acceleration) for comparison. The lowest achieved emittances are ε_{nx} = 1.7 μm and ε_{ny} =1.4 μm (to be compared with ε_{nx} = 4.3 μm and ε_{ny} =6.1 μm with solenoids off, marked with * in the table). With a peak current of 120 A this bunch exibiths the highest beam brightness so far obtained by SPARC injector.

Table 1 – Measured beam parameters

	No Comp.	Comp. ratio 3
Injection phase [deg]	0	-85
Bunch Charge [pC]	300	300
Beam Energy [MeV]	140	100
Energy spread [%]	0.11	1.0
Rms Length [ps]	3.25±0.16	1.03±0.1
ε_{nx} [μm]	2.33 ±0.11	1.74±0.05 4.33 ±0.84 *
ε_{ny} [μm]	1.30 ±0.05	1.44 ±0.03 6.06 ±0.4 *
Solenoid Field [Gauss]	0	400

CONCLUSIONS

In this contribution we show that a successful compensation of the emittance degradation during compression with the Velocity Bunching technique is possible, at least for a moderate compression ratio. This goal has been achieved with a careful tuning of the long solenoids installed around the accelerating sections. A systematic study at higher compression ratios is still in progress. More advanced studies are foreseen in the near future on this subject, including microbunch instability [7], single spike generation in the SPARC FEL [8] and THz radiation production [9].

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