ADVANCED BEAM DYNAMICS EXPERIMENTS AT SPARC

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Abstract

The successful operation of the SPARC injector in the Velocity Bunching (VB) mode has opened new perspectives to conduct advanced beam dynamics experiments with ultra-short electron pulses able to extend the THz spectrum or to drive the FEL in the SASE Single Spike mode. Moreover a new technique called Laser Comb, able to generate a train of short pulses with high repetition rate, has been recently tested in the VB configuration. Up to four electron beam pulses shorter than 300 fs and separated by less than 1 ps have been characterized. In addition two electron beam pulses have been injected in the undulator and a characteristic interference spectrum produced by the FEL interaction in this new configuration has been observed, confirming that both pulses have been correctly matched to the undulator and were both lasing. In this paper we report the experimental results obtained so far.

INTRODUCTION

SPARC is a test facility for high brightness electron beams dynamics studies [1,2,3], FEL physics experiments in SASE, Seeded and new configurations [4,5] and for THz radiation production [6]. The SPARC photoinjector is a 1.6 cell S-band RF gun, followed by 3 S-band accelerating sections , which boost the beam energy up to 150–200 MeV. Downstream the LINAC there are at present two beam lines: the FEL line composed by six undulators, and a parallel line dedicated to a THz source. Other two beam lines are under installation, one for the back-scattering Thomson experiments [7] and the other one dedicated for plasma acceleration experiments [8].

All these applications need very high brightness electron beams, that are produced combining the emittance compensation technique [9] for laminar beams at the gun exit with the low energy RF compression technique, the so called velocity bunching (VB) [10], which requires additional solenoid focusing around the first two accelerating structures to keep under control the emittance growth while bunching.

With this machine configuration a new technique called Laser Comb (LC), aiming to produce a train of short electron bunches, has been proposed [11]. In this operating mode the photocathode is illuminated by a comb-like laser pulse to extract a train of electron bunches which are injected into the same RF bucket of the gun. A typical laser comb time profile at the cathode is shown in Fig. 1. The SPARC laser system, based on a Ti:Sa oscillator is extensively reported in Ref. [12] and related references, while the upgrade required by the laser comb techniques is reported in Ref.[13]. The technique here used relies on a α-cut beta barium borate (α-BBO) birefringent crystal, where the input pulse is decomposed in two orthogonally polarized pulses with a time separation proportional to the crystal length The same laser scheme is also adopted at Tsinghua University [14]
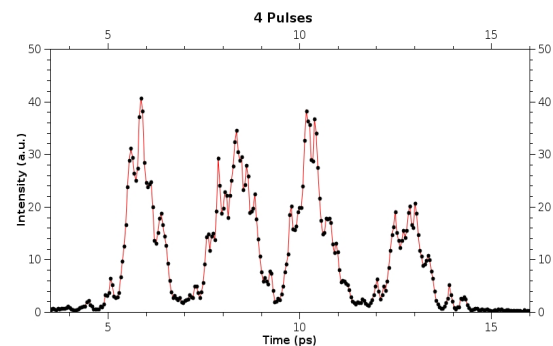

Figure 1: Laser comb time profile at cathode.

In the first accelerating structure, operating in the VB mode, where the bunch train rotates into the longitudinal space phase in order to achieve the desidered time structure, it is possible to control the intra-bunch distance as well as the single bunch length. The final bunch distances and sigle bunch length are infact dependent not only on the laser pulse time structure and extracted charge density from the photocathode but also on the injection phase in the VB. This method preserves all the extracted charge and it is different from other passive tecniques

[15-18], where the train is produced by using a mask that stops a significant fraction of the charge. The laser-comb scheme can be considered to drive fast pump and probe FEL experiments [19], resonant exitation of plasma waves in plasma accelerators [15], sources of narrow-band terahertz radiation [6] and other beam dynamics experiments [18].

Up to four electron beam pulses shorter than 300 fs and separated by less than 1 ps have been characterized and a narrowing THz spectrum produced by the bunch train has been measured. In addition two electron beam pulses have been injected in the undulator and a characteristic interference spectrum produced by the FEL interaction in this new configuration has been observed, confirming that both pulses have been correctly matched to the undulator and were both lasing. In this paper we report the experimental results obtained so far.

THE SPARC LINAC IMPROVEMENTS

When the linac works in VB regime with a relevant compression factor, a very high stability of the machine is very important. The necessary stability has been achieved with VB cooling sistem and RF gun feeding upgrade, with a consequent improvent also of the achieved beam emittance.

New RF Pulse Shaping for RF-Gun Feeding

During previous SPARC runs the RF gun gradient was limited by frequent RF breakdown events in the structure. The incident power was ≈10MW with a 1.5μs RF square pulse (see Fig. 2, blue points), resulting in a beam energy, at the Gun exit, of 4.5 MeV (E_p≈105 MV/m) instead of the nominal one 5.6 MeV (E_p≈120 MV/m). The operating mode with a field lower than the nominal one gave emittance value higher than expected. This limitation has been successfully overcome by a new shaping of the RF pulse (see Fig. 2, red points). In this new configuration during the first three microseconds the RF level is kept at 1 MW to allow the klystron intra-pulse phase stabilization loop transient to work correctly [20] and only in the last microsecond the RF level is led to a larger value, so that the Gun could fill up to the nominal accelerating gradient. In this way the performance of the klystron intra-pulse PLL in terms of phase noise compression is held down to 55 fs$_{RMS}$ inside the gun and the peak amplitude measured in the wave incident to the gun is > 14.5 MW. The gun filling time is 0.7 μs, i.e. the peak power inside the structure is about 76% of the incident

The effect on the beam quality are encouraging. The energy of the beam downstream the Gun is not only restored to the design value, but we could measure a maximum energy greater than 6 MeV (E_p≈130 MV/m) with an emittance at the linac exit dramatically decreased.
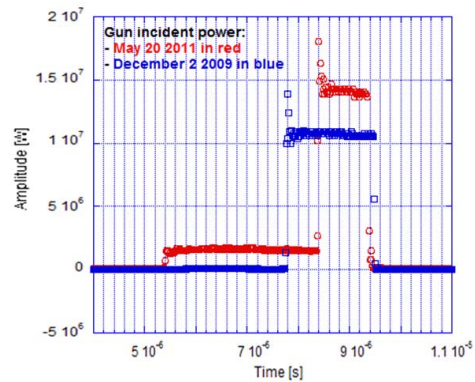

Figure 2: RF Gun pulse profile

Also the vacuum system had some significant benefits; the maximum acceptable breakdown rate has decreased from 5÷6 discharge per minute to less than 1 every 5 minutes, and now 10^{-10}torr vacuum level inside the Gun are maintained during the machine operation.

VB Cavity Long Term Phase Stability

The VB process is strongly sensitive to the RF phase fluctuations by temperature oscillations, resulting in unstable final bunch parameters. From the comb technique this results in an unpredictable distance between the bunches in the train. This distance is a crucial parameter for all the applications and experiments. A major improvement of the VB long term phase stability has been achieved when a dedicated chiller has been installed for the first TW structure. The temperature stability is now within 0.2° Celsius (peak-to-peak), which results in a phase variations lower than 0.2 degrees.

EXPERIMENTAL RESULTS

The measurements presented here have been performed with a train of two and four pulses, by the following procedure: first characterizing the bunches train on the RF crest (0°, maximum energy), then moving the phase of the first TW cavity (φ_{s1}) where VB regime occurs, from the crest value to the phase of maximum compression (90°). At this phase the bunch train length achieves the minimum value corresponding to a full spatial overlapping of all the bunches with a typical total energy separation of about 1 MeV and each electron pulse is also partially compressed. To achieve the foreseen comb structure we have to run in the over-compression regime (typically 94°-95° off crest) so that the bunch distance can be tuned to the designed value and each pulse is near its minimum length [13]. At the linac exit an RF deflecting cavity allows for bunch length measurements with a resolution of 100 fs [21], if the beam is then bent by a dipole it is possible to reconstruct the beam longitudinal phase space. As a reference case we show in Fig. 3 the measured longitudinal phase spaces for two 85 pC bunches (170 pC total charge) running on crest (no compression) in comparison with PARMELA simulations. The agreement is very remarkable also in the details of the phase space distribution. Each pulse results to be 1 ps

long with an energy spread less than 0.1%. The emittance measurements have been performed with the standard quad scan technique at the linac exit that do not allow in the present configuration to separate the contribution of each bunch from the total measured emittance. Nevertheless the total rms emittance of this double pulse results to be 0.97 μm (0.52 μm) including 100% (90%) of particles, in fully agreement with simulations. A very remarkable results that couldn't have been possible to achieve without the SPARC linac improvements described earlier.
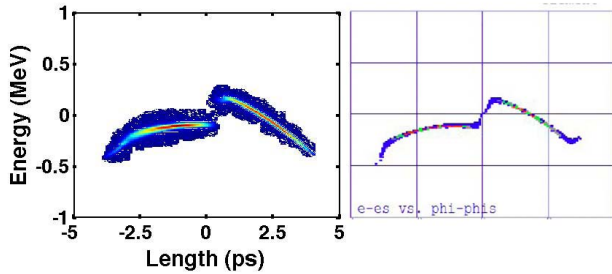

Figure 3: Measured long. phase space on crest (left). The same long. phase space simulated with PARMELA (right)

Two Laser Pulses

In Fig. 4 are shown the longitudinal phase space and the corresponding current profile for a 170 pC total charge beam in the case of maximum compression. As one can see the two pulses are fully time overlapped and behaves like a single bunch. The total peak current is as high as 350 A, corresponding to a total length of 140 fs with a total rms emittance of 4 μm (3.5 μm) with 100% (90%) of particles. This peculiar beam has a total rms energy spread of 0.8 % at 110 MeV at the linac exit, while the energy spread of the first pulse is 0.25% and the second one is 0.4%. It is actually a two energy levels beam, separated by 1.5 MeV, whose properties as a FEL radiation active medium will be investigated soon.
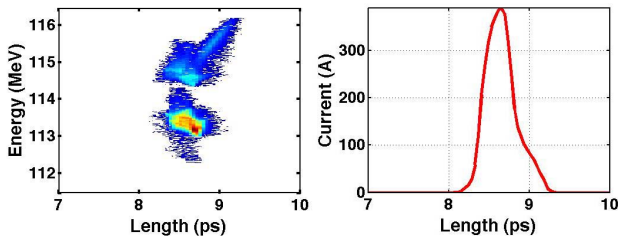

Figure 4: Long. phase space (left) and current profile (right) for a two bunches train (170 pC) at VB phase of maximum compression

Another interesting case is shown in Fig. 5. In this case the VB phase has been set to 95.6 degrees corresponding to the over-compression regime. As expected the two pulses are now well separated by 0.8 ps with a charge unbalance of 10%. The first bunch is 140 fs long and the second one 270 fs long, with a total rms emittance of 6 μm (4.2 μm) with 100% (90%) of particles. It was not the aim of the present experiment to optimize the emittance, so we didn't put enough attention to the fine tuning of the long solenoids, in addition chromatic effects due to the large total energy spread of the train might lead to overestimate the measured emittance.

This configuration has a potential interest to generate two FEL radiation pulses for pump and probe experiments.
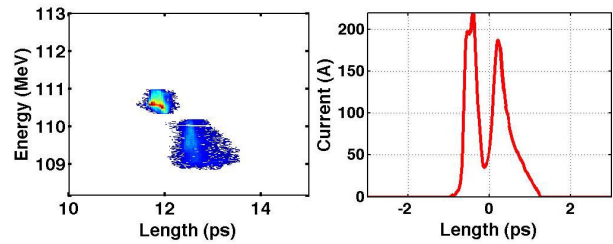

Figure 5: Long. phase space (left) and current profile (right) for a two bunches train (170 pC) at VB phase of over compression

FEL Experiment with Two Bunches

A preliminary experiment with two bunches injected in the undulator has been already done. The train of two bunches, in condition of strong compression, similar to the one shown in Fig. 5, was matched and transported in the SPARC undulator. The main radiation diagnostic was an in vacuum spectrometer [22], an instrument that allows simultaneous single shot measurements of the vertical beam size and of the spectral distributions [5]. The typical spectrum observed, and presented in Fig. 6, is characterized by the presence of regular fringes due to interference of two light pulses produced by the FEL SASE process, being the distance between the peaks larger than the slippage length. By Fourier transforming a radiation composed by two Gaussian wave packets in the time domain, with same widths and amplitudes respectively $A_{1,2}$, separated by an interval δt, the relation between the fringe dimension $\Delta\lambda$ and δt is given by $\delta t = \lambda^2 / \Delta\lambda$. The visibility of the fringes $\eta = I_{max} - I_{min} / (I_{max} + I_{min})$ where I_{max} (I_{min}) is the maximum (minimun) value of the y-average of the spectral amplitude I is moreover connected to the amplitudes of the light pulses by the relation $\eta = 2A_1A_2 / (A_1^2 + A_2^2)$ According to our GENESIS [23] simulations, the measured spectrum shown in Fig 6, corresponds to two light pulses quite well balanced, with and estimated difference between the two peaks of about 30%. The distance between the two pulses turns out to be 0.58 ps. As the measurements were performed in non optimal experimental conditions only 40% of the spectra collected shows regular fringes, while 48% presents signature of the amplification of one single bunch and the remaining 12% is strongly affected by noise. The average made on the significative part of 200 measured events leads to a pulse to pulse distance of $\delta t = 0.615 \pm 0.155$ ps, to be compared with the measured electron bunch

separation of $\delta t = 0.809 \pm 0.053$ ps.

This result that deserve a more systematic study that will be done during the next SPARC run. Nevertheless the characteristic interference spectrum produced by the FEL interaction in this new configuration indicates that both pulses have been correctly matched to the undulator and were both lasing.
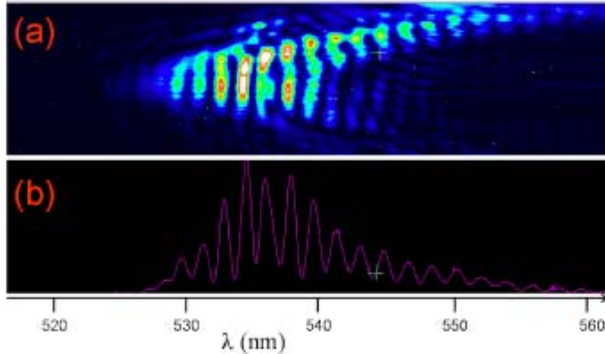

Figure 6: (a) Single shot spectrum measurement in the case of radiation from two bunches starting from noise. The ordinate is the transverse dimension coordinate y. (b) Average value along y of the spectral intensity I. In this case the width of the fringes turns out to be $\Delta\lambda = 1.66$ nm and their visibility $\eta = 0.67$

Four Laser Pulses

The four pulses configuration needs to run the VB in a deep over-compression regime, which is well over the maximum compression value. It is necessary to perform a major rotation of the longitudinal phase space to separate the four bunches in the region of balanced current. The total emittance has been measured for a total charge of 200 pC (with a charge distribution among the 4 bunches of 13%, 25%, 40%, 22%) in three configurations: on crest, compression and over-compression, giving respectively, 1.1 μm, 4.0 μm and 4.1 μm at 90% of particles.
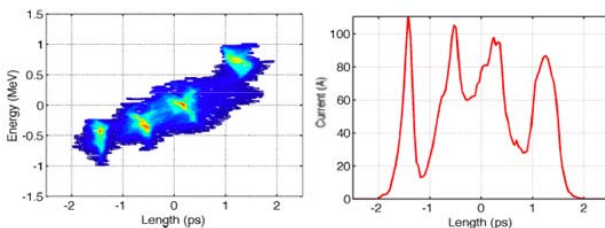

Figure 7: Long. phase space (left) and current profile (right) for a four bunches train (200 pC) at VB phase of deep over compression (107.9 degrees)

Fig. 7 shows the longitudinal phase space and the current profile for the over-compression regime with injection phase in the VB 108 degrees off crest. Four spikes spaced by 0.9 ps are clearly visible. The whole bunch train is 3.5 ps long with four bunches of length 140 fs, 200 fs, 280 fs and 230 fs . This time structure has been used in a test experiment to produce narrow band, tunable THz radiation.

Narrow Band TH Radiation

Narrow band, tunable THz radiation is produced at SPARC combining the VB technique and the comb-like electron beam distribution [6].

A Martin-Puplett interferometer has been installed at the THz station to allow the measurement of the autocorrelation of the radiation pulse (the interferogram), which represents the autocorrelation of the particle distribution. The coherent transition radiation (CTR) spectrum is directly provided by Fourier transforming the autocorrelation function. For a comb beam, the interferogram shows 2N-1 peaks (where N is the number of bunches in the train) whose distance provides the inter-distance of the bunches in the train. Hence the spectrum of the radiation is strongly suppressed outside the comb repetition frequency.

An example of the measured autocorrelation function for a train of N=4 pulses is presented in Fig. 8. The peak distance of 0.9 ps corresponds to the bunch-to-bunch separation. The frequency spectrum shows an enhancement of the emission around 0.8 THz.
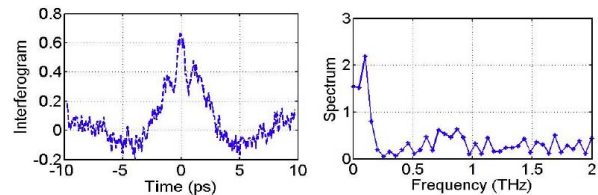

Figure 8: The autocorrelation function measured for the four bunches trainand the corresponding frequency spectrum.

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