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Two Color FEL driven by a Comb-like Electron Beam Distribution

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Abstract

We discuss a new method for the production of trains of FEL radiation pulses based on the FEL emission driven by a comb-like electron beam. In addition, we present recent experimental results on the two color FEL emission as generated at the SPARC_LAB facility: a train of two short (<200 fs) electron bunches, almost overlapped in time, with a comb-like energy distribution, has been injected in the undulator, giving rise to FEL pulses at two characteristic frequencies with multi-peaked time structure. This scheme shows also the versatility of the SPARC photo-injector to generate and manipulate such energy and time distributions.

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Keywords: Free-Electron Laser; Velocity bunching; Laser Comb

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1. Introduction

A comb beam is an electron pulse train with sub-picosecond length and adjustable sub-picosecond inter-distance; such beam has a wide spectrum of applications such as coherent excitation of plasma waves in plasma accelerators, ultrafast pump-probe Free-Electron Laser (FEL) experiments and generation of narrow-band THz radiation.

Concerning the generation of comb beams, passive techniques to tailor the current profile based on the use of intercepting masks placed in a magnetic system have been proposed and tested (Muggli et al. (2008), Muggli et al. (2010), Piot et al. (2011)). One of the limitations of these methods is the loss of a consistent portion of the beam due to the masking. An alternative, completely active, method has been proposed in the last years (Boscolo et al. (2007), Ferrario et al. (2011)). 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 a magnetic compressor with negative R_{56}. Downstream the gun, the initial density modulation is converted, due to space charge, in energy modulation, that after compression is transformed back in charge density modulation. The train parameters are completely controlled by the accelerator with virtually no particle losses, giving the possibility to produce high charge pulse trains. The method, after extensive numerical simulations optimizing the working parameters, has been successfully demonstrated in terms of reliability and reproducibility in a full “velocity bunching” scheme at SPARC (Ferrario et al. (2010)).

Concerning the experiment presented in this paper, a train of two 200 fs electron bunches, almost overlapped in time, with a two-level energy distribution, has been injected in the SPARC undulator, resulting into FEL pulses at two characteristic frequencies with multi-peaked time structure. Trains of high brightness, picosecond spaced, electron pulses are meant to be used at SPARC_LAB (Ferrario et al. (2013)) as source for FEL as well as novel plasma-based accelerators and advanced radiation sources.

A growing interest, in particular in the production of two color FEL radiation is documented by experiments performed worldwide, e.g. at LCLS (Lutman et al. (2013)), FERMI (De Ninno et al. (2013)), leading to the investigation of different methods of generation of two-level FEL energy spectra.

To overcome the limitation concerning the natural bandwidth of the FEL amplifier, a two-bunches electron beam, with a given time and energy separation, needs to be produced and controlled in order to be matched into the undulator. One method, the one we adopt at SPARC_LAB, for tailoring the time and frequency separation of the FEL pulses, relies on the application of the laser comb technique in the velocity bunching (VB) regime. This method allows exploring several aspects of the FEL dynamics: ultra-short pulse trains at two frequencies, two color or one color radiation at two different times.

In particular, two-bunch trains, with given time separation and a double peaked energy distribution, defined by operating the first linac section in velocity bunching, have been matched to the FEL undulator. The natural bandwidth of the undulator radiation is described by the Pierce parameter, ρ (Bonifacio et al. (1984)). SASE FEL lasing occurs from two separated and nearly independent electron distributions, at two separate frequencies, if

- the relative energy separation is larger than ρ,
- the sub-bunches energy spread of the order or less than ρ,
- the sub-bunches length smaller than the cooperation length, L_c,

The longitudinal phase space of such a comb-like distribution has been fully characterized together with the produced FEL pulses in time and frequency domain.

2. The SPARC_LAB Test Facility

The SPARC_LAB test facility hosts a 180 MeV high brightness electron beam injector (Ferrario et al. (2007)), able to operate also in the velocity bunching configuration (Ferrario et al. (2010)), which feeds a 6 sections, 12 meters long undulator. Observations of FEL radiation in the SASE (Giannessi et al. (2011)), Seeded (Labat et al. (2011)) and High Order Harmonics Generation (Giannessi et al. (2012)) modes have been reported from 800 nm down to 40 nm wavelength, both with a single and a two-bunches train.

A second beam line is used as test bench beam line for THz radiation (Chiadroni et al. (2013)), Electro-Optical Sampling studies (Pompili et al. (2013)) and advanced beam position monitor research. In addition, to the electron beamlines, a laser beamline links the multi-hundreds TW laser FLAME to the linac, allowing to explore laser-matter interaction, through the Thomson back-scattering experiment, and laser-plasma acceleration of electrons (Gizzi et al. (2009)) (and protons) in the self-injection and external injection schemes. The facility will be also used for particle driven plasma acceleration experiments, by means of a train of ultra-short high brightness electron bunches (Ferrario et al. (2011)) to excite coherent plasma waves in plasma accelerators. A cartoon of the SPARC_LAB activities is shown in Fig. 1.

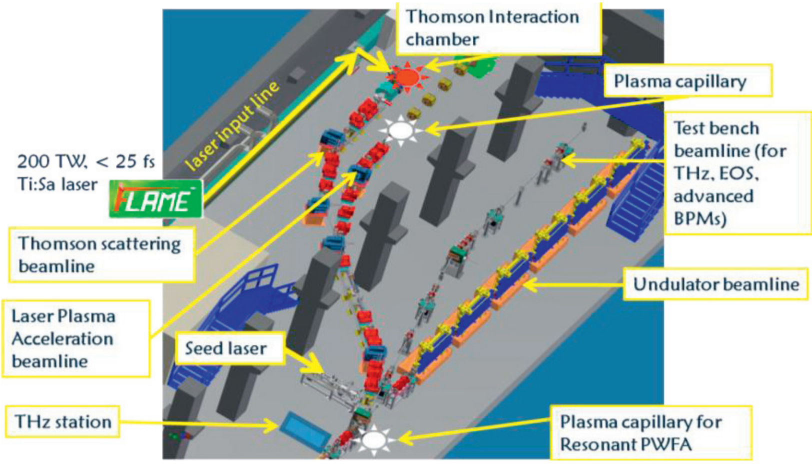


Fig. 1. Layout of the SPARC_LAB test facility.

The electron beam is characterized both transversely and longitudinally in the diagnostics transfer line placed at the end of the linac. This section consists of two quadrupole triplets for matching the electron beam into the undulator or to the other beamlines. The first triplet is also used for quadrupole scan based emittance measurements (Mostacci et al. (2012)). The RF deflecting cavity (Alesini et al. (2006)) and the dipole spectrometer allow to fully define the beam Longitudinal Phase Space (LPS) (Filippetto et al. (2011)).

The FEL photon diagnostics consists in a Ocean Optics spectrometer with 1.2 nm resolution at 800 nm, a joulemeter (Molectron J3-S, 5.96E8 V/J @ 1μm) and a NIR-Grenouille FROG device (time-bandwidth product <10; spectral resolution 0.7 nm at 800 nm; single-shot sensitivity 1 μJ). In particular, the spectral window of this device sets a constraint on the beam energy for lasing around 800 nm. A 45 deg mirror placed in the last undulator chamber allows the extraction of the radiation normally to the beam axis. FEL radiation is then collected and reflected to a movable mirror, which directs it alternatively to each instrument.

2.1. Generation and Manipulation of comb-like electron beams

The technique used at SPARC_LAB to generate a train of electron bunches, the so-called comb beam, relies on the use of a birefringent crystal, where the input UV pulse is decomposed into two orthogonally polarized pulses with a time separation, in the order of ps, proportional to the crystal length. A ps-spaced comb laser pulse illuminating the metallic photocathode in the RF gun generates a train of electron bunches with the same time separation. The beam, accelerated to an energy of about 5.8 MeV in the RF gun, is then injected in the first linac section S1. In the drift downstream the RF gun, the beamlets undergo a broadening due to space charge effects with a correspondent energy modulation. Then, a dispersive section, i.e. S1 working as RF compressor, will force a time energy rotation in the LPS, restoring a density modulation with bunch time separation depending on the S1 compression phase.

The main advantage of such method is that the train parameters, i.e. bunch charge, length, and inter-distance, are completely set and controlled by the accelerator, once defined the crystal length, with virtually no particle losses.

2.2. Experimental configuration

We consider the case of two bunches in the train. The TSTEP simulation reported in Fig. 2 shows the evolution of the compression factor as function of the RF phase of the first linac section.

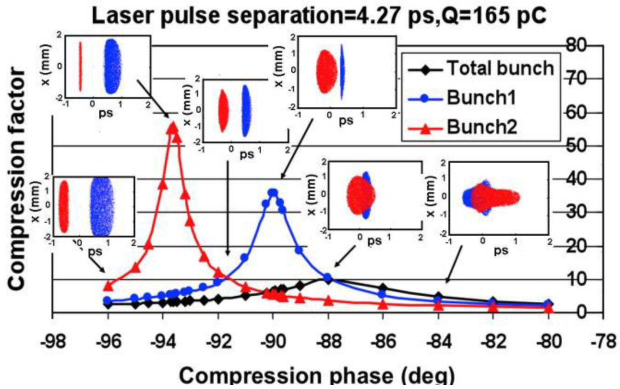


Fig. 2. TSTEP simulation showing the compression factor as function of the compression phase, i.e. the RF phase of the first accelerating section, for a two-bunches train with total charge of 165 pC.

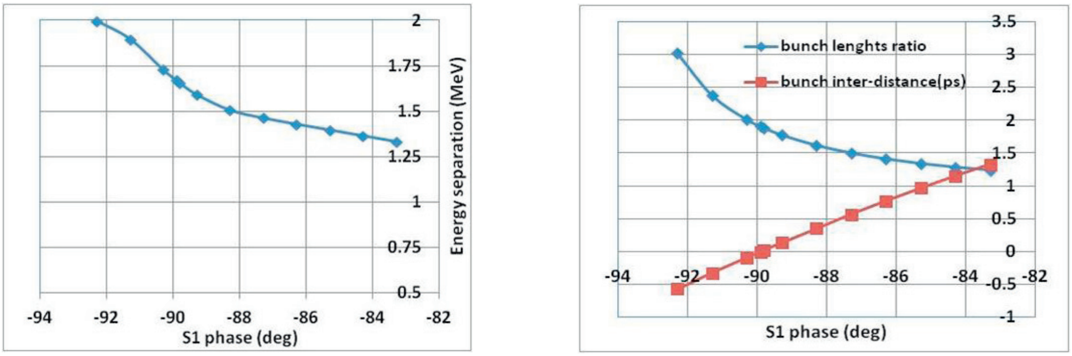
The black curve represents the whole bunch compression curve while the red and blue ones are those of each bunch in the train. Three regimes of compression for the whole bunch can be highlighted, going from the right hand to the left end of Fig. 2. The moderate compression region, lying between -80 deg and -88 deg, where the two bunches get closer but are still too long to be considered as separated in time, thus there is only a (time) modulation in the bunch. Then there is the maximum compression region, around -88 deg, where the whole bunch has the minimum length and the two bunches are squeezed and superimposed in time. Eventually the over compression region, beyond -90 deg, where the two bunches have short duration and are well separated in time.

The range on time and energy separation depends on how much they are separated initially, i.e. it is fixed by the crystal length and by the given charge. Within this range the LPS can be tune to adjust time and energy separation by changing the linac settings.

The experimental results presented in the next section concern a two-bunches beam with 4.27 ps bunch inter-distance at the cathode, 160 pC total charge and 90 MeV energy when operating the first linac section off-crest to provide RF compression.

3. FEL experiments with two bunches in the macro-pulse

The regime close to the maximum compression, between -84 deg and -88 deg, has been extensively investigated for FEL experiments concerning the production of trains of FEL radiation pulses with two-level energy spectra. Depending on the compression phase, the TSTEP simulation shows that the energy separation is in the 1 MeV range (Fig. 3a), while the main effect is on the bunch inter-distance (Fig. 3b). However, the two bunches are not separated in time in this region, as shown in Fig. 4 (insets a) and b)), but they cross each other moving down to the maximum compression phase, where they are well overlapped (inset c)). Figure 4d) clearly shows that moving further towards the over-compression region the two bunches interchange each other and start to increase their inter-distance.



a) b)

Fig. 3. TSTEP simulation for a two-bunch beam with total charge 165 pC and laser pulse separation 4.27 ps: a) computed two-bunch energy separation and b) bunch lengths ratio and bunch inter-distance versus S1 phase.

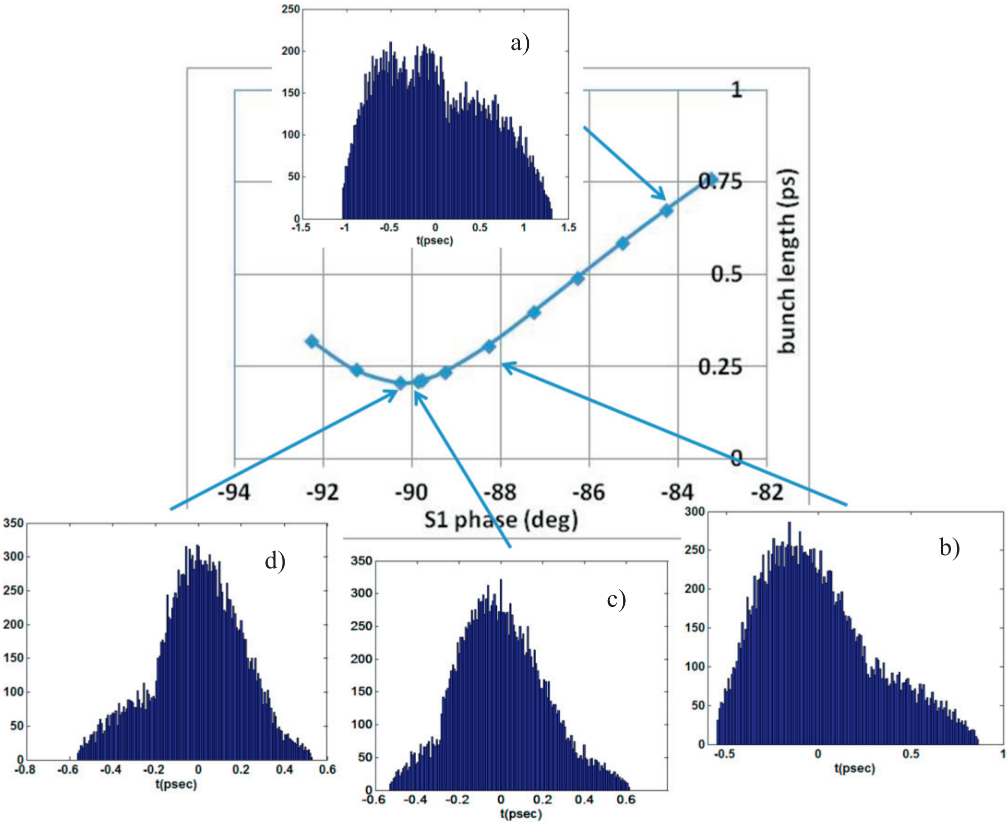


Fig. 4. TSTEP simulation for a two-bunch beam with total charge 165 pC and laser pulse separation 4.27 ps: computed whole bunch length versus S1 phase. The insets shows the whole bunch current profile (vertical axis is in Amps) in case of moderate compression (a), for S1 phase close to the maximum compression (b), at the maximum compression (c) and for moderate over-compression (d).

The experimental LPS referring to these points are shown in Fig. 5, where moving along the compression curve the two bunches get closer and shorter (Fig.5a), up to the maximum compression phase where they are almost temporary overlapped (Fig. 5b). Moving further to the over-compression region they get clearly well separated in time (Fig. 5c).

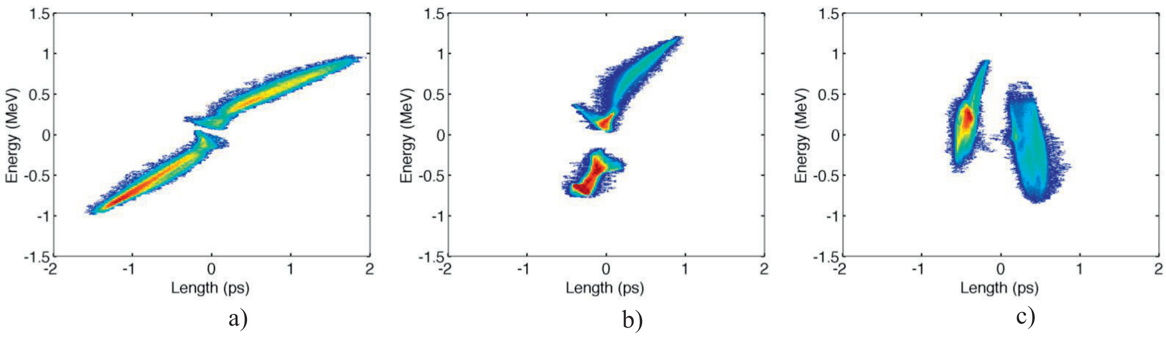


Fig. 5. Experimental LPS for two-bunch beam with total charge 165 pC and laser pulse separation 4.27 ps, as measured for three different S1 phase distinctive of the three compression regions, i.e. a) moderate compression, b) maximum compression, c) over-compression.

The achieved beam parameters for the machine settings referring to the quasi-maximum compression (Fig. 5b) are listed in Table 1.

Table 1. Electron beam parameters for the quasi-maximum compression.

Whole beam		Single bunch	
Peak current (A)	300	250	140
Bunch duration (fs)	300	100	250
Normalized emittance (mm mrad)	1.7 (0.1)		
Energy spread (%)	0.6	0.2	0.3
Energy (MeV)	93.038(0.032)	92.515(0.033)	93.588(0.033)
Energy separation (MeV)	1.07		
Time separation (ps)	0.417(0.029)		

The two sub-bunches, so produced with two energy levels (γ_i), when injected in the undulator, act as independent radiation sources with central resonance wavelength given by

$$\lambda_{r,i} = \frac{\lambda_u}{2\gamma_i^2}\left(1 + K_{rms}^2\right) \qquad i = 1,2 \quad , \tag{1}$$

λ_u is the undulator period and K_{rms} is the normalized, dimensionless rms undulator parameter. In addition, if the electron beam width L_b is shorter than 2π times the cooperation length L_c, defined as

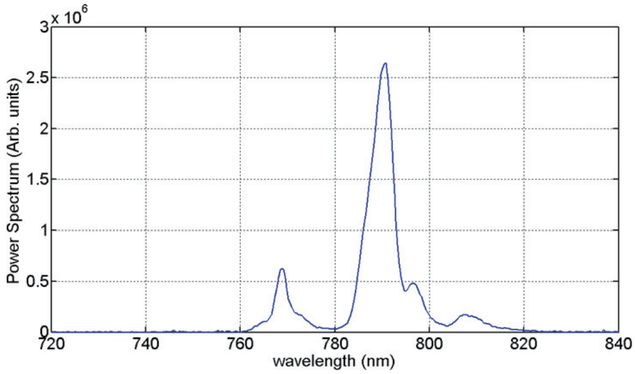
$$L_c = \frac{\lambda_r}{4\pi\sqrt{3}\rho} \quad , \tag{2}$$

then the FEL emission occurs in single spike regime with the output radiation characterized by nearly transform-limited pulses. Moreover, when the two pulses are overlapped in time, they interfere, resulting in beating fringes in the time domain whose separation is given by

$$\Delta T = \frac{\lambda_r^2}{c\left(\lambda_{r,2} - \lambda_{r,1}\right)} \quad (3)$$

The total radiation bandwidth is now set by the electron energy separation and not by ρ, thus enabling the formation of very short temporal structures. The Fourier analysis for a spectrally double-peaked radiation pulse yields a sinusoidally varying intensity profile where the time separation of the fringes ΔT depends on the difference in energy of the bunches through $\lambda_{r,i}$.

Undulator parameters are adjusted such that fundamental FEL resonance occurs at 800 nm, in order to allow the spectro-temporal beam diagnostics available at SPARC_LAB. Data were acquired in different compression conditions of the electron beam. The FEL single shot spectrum shows in Fig. 6, together with the multi-shot analysis to retrieve the spectral characteristics, refers to experimental beam parameters summarized in Table I.



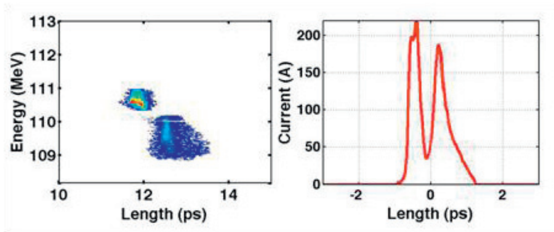
λ_{min} (nm)	769.8 (2)
$BW_{\lambda min}$ (%)	0.5
λ_{Max} (nm)	788.6 (1.3)
$BW_{\lambda Max}$ (%)	0.7
$\Delta\lambda$ (nm)	18.8 (2.9)
ΔE (MeV)	1.1 (0.17)
FEL Energy	> 37 μJ

Fig. 6. Single shot two-colour FEL spectrum, with listed parameters as retrieved from the multi-shot analysis.

A detailed description of the spectro-temporal properties of the multi-peaked electron energy distribution shown here can be found in Petrillo et al., 2013.

3.1. Versatility of beam manipulation

In a previous experiment we have characterized the two-bunches electron beam in the over compression regime, where as shown in Fig. 6. The electron beam matching and transported to the undulator was adjusted such that fundamental FEL resonance occurred at 520 nm.



a) b)

Fig. 7. (a) Experimental LPS for a two bunches train (165 pC) at VB phase of over compression and corresponding double-peaked current profile with 0.8 ps time separation.

The main radiation diagnostic was an in vacuum spectrometer (Poletto et al. (2004)), which allowed simultaneous single shot measurements of both vertical beam size and spectral distributions (Giannessi et al. (2011)). The typical measured spectrum, reported in Fig. 7, 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,.

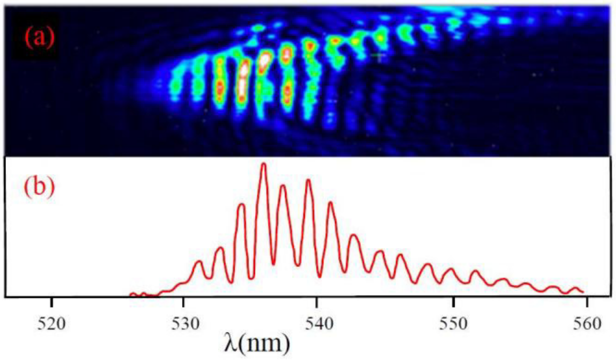


Fig. 8. (a) Single shot spectrum measurement in the case of radiation from two bunches starting from noise. The ordinate is the transverse dimension coordinate y. (b) Average value along y of the spectral intensity *I*. In this case the width of the fringes turns out to be $\Delta\lambda = 1.66$ nm and their visibility $\eta = 0.67$.

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 δ, the relation between the fringe dimension $\Delta\lambda$ and δ is given by $\delta = \lambda^2/\Delta\lambda$. The visibility of the fringes $\eta = (I_{max}-I_{min})(I_{max}+I_{min})$, where I_{max} (I_{min}) is the maximum (minimum) value of the y-average of the spectral amplitude. In addition, I is connected to the amplitudes of the light pulses by the relation $\eta = 2A_1A_2/(A^2_1+A^2_2)$. According to GENESIS (Reiche (1999)) simulations, the measured spectrum, shown in Fig. 7, corresponds to two well balanced light pulses, with an estimated difference between the two peaks of about 30%. The distance between the two pulses turns out to be 0.58 ps. The average made on the significant part of 200 measured events leads to a pulse-to-pulse distance of δ = 0.615±0.155 ps, to be compared with the measured electron bunch separation of δ = 0.843±0.100 ps. The characteristic interference spectrum produced by the FEL interaction in this two bunches configuration indicates that both pulses have been properly matched to the undulator and were both concurring to the lasing.

4. Conclusions

We reported on the production and characterization of trains of FEL radiation pulses with two-level energy spectra based on the FEL emission driven by a two-bunches electron beam with time and energy separation tunable with linac settings. These experimental results demonstrate also the ability of manipulating both the properties and the quality of such beams, being of utmost importance not only for FEL applications, but also for future plasma acceleration experiments at SPARC_LAB.

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