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Recent results of the SPARC free-electron laser

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Summary. — In this paper we report recent results obtained with the velocity bunching compression technique and the relative FEL experiment of the SPARC collaboration. The beam compression allows to work with short beam and high peak current without emittance growing, but it also induces a correlated energy chirp along the beam. The FEL experiment demonstrates the possibility of compensating the induced effects of the energy chirp by a proper taper of the undulator gaps. The typical chaotic spiking in the spectrum of the Self Amplified Spontaneous Emission (SASE) regime observed with untapered undulator is converted in a single longitudinal mode. This regime is called Single Spike SASE regime.

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1. – Introduction

The SPARC (Sorgente Pulsata Autoamplificata di Radiazione Coerente) project [1] is a research and development experiment for high brightness electron beam photo-injectors at the LNF, Frascati (Italy). The SPARC FEL machine, showed in fig. 1, is composed by a high brightness photo-injector providing a high-quality beam at energies up to 150 and 200 MeV (12 m), a transfer line for beam matching and diagnostic (6.8 m) and an undulator beam line (13 m) composed by six undulator sections with variable gap. The photo-injector is based on a 1.6 cell S-band RF gun follows by three RF accelerating sections. A Ti:Sapphire laser at 800 nm is up-converted to 266.7 nm, shaped, and sent to the copper cathode of the RF gun. The first two sections are surrounded by solenoids providing additional focusing during acceleration. The beam is characterized by variable bunch length with extremely low emittance $\epsilon_n < 2\,\text{mm}\,\text{mrad}$ and high current $I > 100$ A, *i.e.* high brilliance $B = 2I/\epsilon_n^2$. The electron beam injected through the undulator generates high brilliance and tunable FEL radiation in the visible region around the fundamental wavelength (500 nm) and at VUV wavelengths with the harmonics. The

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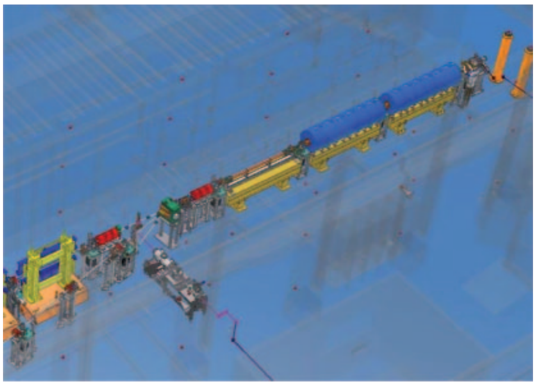

Fig. 1. – Layout of SPARC linac, matching section and the first of the six FEL undulator sections.

emitted wavelength is given by the resonant condition $\lambda_R = \lambda_u/(2\gamma^2)\cdot(1+K^2/2)$, where λ_u and $K = eB_u\lambda_u/(2\pi m_e c)$ are, respectively, the undulator wavelength and strength, and γ is the Lorentz factor. The SASE FEL interaction uses the broadband signal of the spontaneous emission to start the FEL amplification. The SASE is a longitudinal quasi-coherent pulse. The time structure is composed by many regions (spikes) that are independent of one another. This is due to the different velocity of the radiation and the electron beam. The electrons are causally connected only within the part of the beam, reached by the light emitted by themselves. Therefore the temporal profile and the spectrum are composed by many spikes. To obtain a full coherent laser pulse a seed pulse is needed or, in SASE mode, it can be done with very short electron bunches, *i.e.* a bunch length as long as the region of the beam that radiates coherently due to the FEL interaction. The regime is called the Single Spike regime and its importance is due to the great interest in the generation of probe in femtosecond scale especially for X-ray range. This ultrafast probe allows the direct observation of structural dynamics involved in matter physics, chemistry and biology. Consequently the basic idea is to compress the beam until the Single Spike regime is achieved, but the classical magnetic compression produces an unacceptable degradation of the beam brilliance. The velocity bunching (VB) compression mechanism, instead, preserves the beam quality but it introduces a linear chirp along the electron bunch and the compression ratio must be chosen accurately in order to have the maximum brilliance (a brief description of the VB technique is presented in the next subsection). With this kind of bunch we use the idea first proposed in ref. [2], where short energy chirped electron beams are injected into a tapered undulator to compensate the chirp. This scheme allows to select the brightest region of the bunch to operate in the Single Spike regime.

In May 2010 the first full coherent pulses of SASE-FEL in SASE Single Spike regime were observed with the maximum energy ever obtained at SPARC [3]. The generated pulses are fully coherent, and they have a length shorter than the electron beam length, so their duration can reach the femtosecond scale. The interesting aspect of this regime is that the single spike can be achieved also with an electron beam longer than the single spike length. In fact, already in the visible range the theoretical single spike length is of the order of few hundreds fs, while in the X-ray regime it can be lower than 1 fs. The simulation results show the same behaviour of the experiments with the

Table I. – *Main parameters for compressed and uncompressed beams.*

Parameter	Compressed($C = 5$)	Uncompressed
Energy [MeV]	~ 115.2	~ 180
Energy Spread [%]	0.3	0.03
Energy Chirp [keV/μm]	6 ± 1.5	0
Norm. Emittance [mm-mrad]	2–3	1–2
Beam length [ps]	0.42	2
Beam Peak Current [A]	380	80

formation of a single coherent spike, and there is a good agreement between simulation and experiment [4].

1·1. *Velocity Bunching compression technique.* – Space charge effects at low energy prevent the generation of short electron bunches (< 1 ps) with a significant amount of charge (> 10 pC) directly from the electron source, leading to emittance degradation and bunch elongation within a few centimeters downstream the cathode. As such, bunch compression is always necessary to shorten the electron pulse to the required length thus achieving a high peak current. The velocity bunching technique is a method for compressing an electron bunch by means of electromagnetic fields of an accelerating cavity [5].

This is possible if the injected beam velocity is slightly slower than the phase velocity of the RF wave so that when injected at the zero crossing field phase it slips back to phases where the field is accelerating, but is simultaneously chirped and compressed. This mechanism occurs in the first accelerating section and can lead to a compression factor above 10. Code simulations have shown the possibility to fully compensate the transverse emittance growth during RF compression, and this regime has been experimentally proven at SPARC [6]. A parameters comparison between uncompressed and compressed beam is shown in table I.

2. – FEL experiment with compressed beam

The effect of the chirp on the gain can be compensated by tapering the undulator [2]. The compensation mechanism can be explained analysing the diagrams shown at left in fig. 2. The pictures represent the propagation of a field spike (green) developing on the rear part of a chirped e-beam (light blue). The vertical axis represents the resonant condition which depends on the relative position between the beam and the radiation. The upper diagram is relative to the untapered case. When the beam propagates through the undulator, the slippage process leads the spike out of resonance. When the chirp is combined with an appropriate undulator taper (lower diagram), the resonance condition can be preserved. The resonant wavelength for an energy chirped electron beam is a function of the position along the undulator. For a linear chirp along the bunch we may define the local mean energy as $m_e c^2 \gamma(s) = m_e c^2 \gamma_0 + \alpha(s - s_0)$, where s corresponds to the longitudinal coordinate along the electron bunch centred in s_0 in a reference frame drifting at the velocity $\beta_{\|}$. The parameter α defines the slope of the average slice energy *vs.* the coordinate s. The different velocity of the light with respect to the electrons brings a radiation spike building up in a given position, out of resonance when it slips of a distance of the order of $\delta s \approx m_e c^2 \rho\gamma/(2\alpha)$. For this reason an inhomogeneous gain

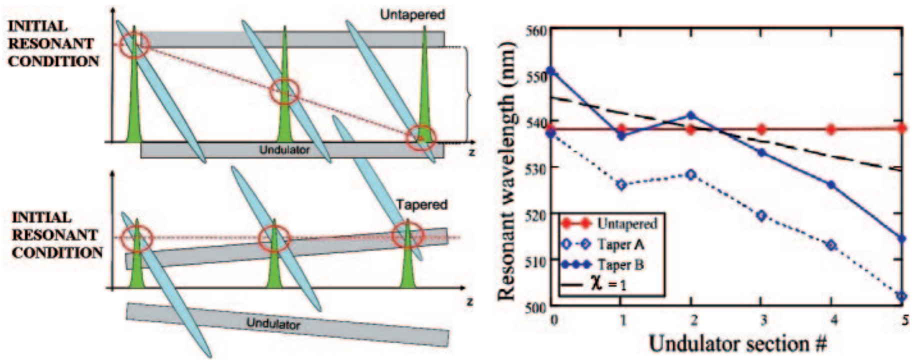

Fig. 2. – (Colour on-line) The pictures in the left panel represent the propagation of a field spike (green) developing on the rear part of a chirped e-beam (light blue). The upper diagram is relevant to the untapered case, the lower one to the tapered case. In the picture in the right panel the red line is the untapered K value to laser at 540 nm with the mean energy value. The black dashed line is the theoretical scaling taper given by eq. (2) with $\chi = 1$. The procedure to choice the undulator gaps are in order to minimize the bandwidth (blue dashed line). The shifted curve (blue full line) is to compensate the blue shift observed during the experiment and is the same used in the simulations.

broadening, associated to energy spread, is expected even with a negligible local energy spread because of slippage. A taper of the undulator may be used to compensate the effect of energy dispersion associated to the pulse slippage on the chirped beam. The energy change caused by the chirp and observed at the peak of the radiation pulse may be expressed as

$$m_e c^2 \gamma(z) = m_e c^2 \gamma_0 + \chi \alpha z \frac{\lambda_r}{\lambda_u}\,, \tag{1}$$

where z is the coordinate along the undulator, γ_0 is the Lorentz factor at the undulator entrance ($z = 0$), at the position along the bunch where the spike will grow, and where χ is a coefficient accounting for an arbitrary propagation velocity of the radiation v_s. For $v_s = c$ we have $\chi = 1$. The field in presence of gain propagates at a velocity lower than c, the peak of a spike in the exponential gain regime is expected to move at a velocity given by [7] $v_s = \frac{3v_\parallel}{2+v_\parallel/c}$. In this last case we have $\chi = 1/3$. Inserting eq. (1) in the resonant condition and solving for the undulator K we obtain a taper scaling which preserves the resonance condition during propagation

$$K(z) = \sqrt{2\left[\frac{\lambda_r}{\pi}\left(\gamma_0 + \alpha\chi z\frac{\lambda_r}{\lambda_u}\right)^2 - 1\right]}\,. \tag{2}$$

The technique used to compensate the chirp with the taper was that of progressively closing the gaps one module at the time, starting from the first one while observing the emitted spectrum. For each module we found the gap minimizing the spectral width. During this procedure we observed a blueshift of the resonant frequency and in order to compensate it we opened more the first sections of the undulator. This procedure lead to the set of gaps corresponding to the resonance frequencies (at 116 MeV) shown in

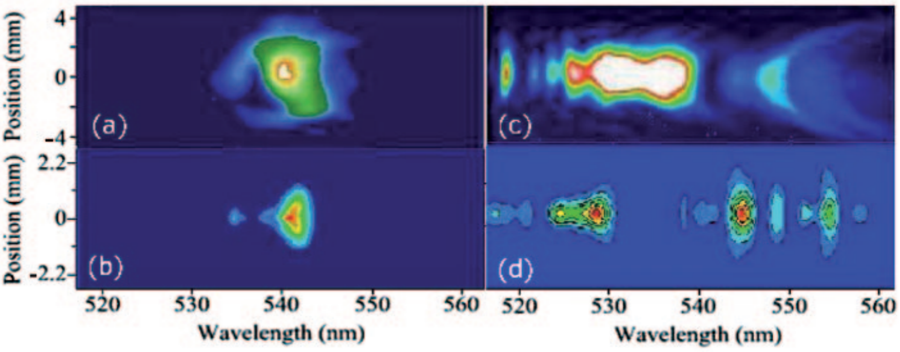

Fig. 3. – (a): Experimental Single Spike spectrum with tapered configuration. (b): Reconstructed Single Spike spectrum with tapered configuration (simulation). (c): Experimental multispike spectrum with untapered configuration. (d): Reconstructed spectrum with untapered configuration (simulation).

fig. 2, where the changes in the gaps is shown, *i.e.* the resonant wavelength, that allowed to minimize the bandwidth (fig. 2 (Taper A)) and the taper shift that compensates the blueshift (fig. 2 (Taper B)). The theoretical scaling given by eq. (2), with $\chi = 1$, is the dashed line in fig. 2. After the tapering procedure, with the resonant frequency per undulator as shown in fig. 2, we have obtained a substantial increase of the pulse energy which reached 140 μJ with a standard deviation of about 100 μJ and a reduction of the average linewidth which was $8 \cdot 10^{-3}$ averaged over 100 pulses. Without tapering the average pulse energy obtained is 7.8 μJ and an average linewidth of 1.5%. Several spectra in the acquired set were characterized by a spectral pattern similar to the one shown in fig. 3(a), constituted by a single coherence region (no multiple SASE spikes). The pulse energy in the spectrum of fig. 3(a) is about 260 μJ.

The field data generated by GENESIS code [8] have been post processed through a numerical procedure resembling the slit/grating/CCD of the spectra detection system, the spectrum in tapered and untapered configuration are shown, respectively, in fig. 3(b)–(d), the horizontal axis is centred at 540 nm and the width is 45 nm. In the tapered configuration the mean energy is about 20 times the untapered one, while the bandwidth is halved. The mean energy simulated is about 130 μJ which is comparable with the experimental (140 μJ), a spectral width of 1.5 nm and the RMS length of about 45 fs. The agreement with the experimental results is quite good and the spectrum is composed by a single coherent region.

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