Seeding experiments at SPARC


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A R T I C L E   I N F O

Keywords:
Free-electron laser
Harmonics
Harmonic generation
Superradiance
Non-linear dynamics

A B S T R A C T

In the framework of the DS4 EUROFEL collaboration, a research work plan at the SPARC free-electron laser (FEL) test facility aiming at the investigation of seeded and cascaded FEL configurations is under implementation. The main goal of the collaboration is to study and test the amplification and the FEL harmonic generation process of an input seed signal obtained as higher-order harmonics generated both in crystals (400 and 266 nm) and in gases (266, 160, 114 nm). The SPARC FEL can be configured to test several cascaded FEL configurations. In this paper we introduce SPARC and its main parameters and we analyze the superradiant cascade and the harmonic cascade seeded with a signal with the typical time structure of the harmonics generated in gas.

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1. Introduction

The SPARC [1] experiment provides a new and exciting opportunity to study free-electron laser (FEL) dynamics in seeded configurations. Several schemes aimed at the generation of radiation at short wavelength will be tried for the first time and the commissioning of SPARC comes at an opportune time since it will allow us to test and develop these new techniques in preparation of the SPARX short-wavelength light source.

Seeded FELs offer several advantages with respect to self-amplified spontaneous emission (SASE) [2–5] in terms of stability and coherence length. When the seed is combined with an undulator cascade, these advantages may be extended to the harmonics of the seed. In a cascaded FEL configuration, the undulator is generally composed by two sections, where the beam is modulated in energy in the first (modulator) and is then injected in a radiator tuned at a higher harmonic of the first [6–8]. This configuration has demonstrated the capability of extending the FEL operating wavelength in the UV range while preserving the spectral properties of the seed along the cascade [9,10]. Multiple-stage cascades have been proposed in order to further extend the range of operation to even shorter wavelengths and recently other schemes based on the evolution of radiation pulses in multiple-stage cascades in superradiant regime [11–14] have been proposed [13]. It has been indeed demonstrated that a solitary wave-like configuration of fields and modulation of the
beam current may be induced, which has the special property while passing from one undulator with a given resonance to a second one resonant on an higher harmonic of re-generating itself at the new frequency.

Frequency up-conversion may also be obtained at the seed source level. Different schemes of non-linear harmonic generation may be implemented to generate the shorter wavelength radiation for seeding the FEL. Second and third harmonic of a Ti:Sa laser source may be efficiently generated in LBO crystals and shorter wavelengths may be obtained with the technique based on the generation of very high harmonics in gas (HHG) [15,16]. The higher-order harmonics result from the strong non-linear polarization induced on rare gases atoms, such as Ar, Xe, Ne and He, by the focused intense electromagnetic field of the “pump” laser. The emitted pulse is composed by a sequence of short bursts separated by one half of the fundamental laser period (400 nm) and the spectrum contains the odd harmonics of the original laser. This method extends the seed source spectral range down to the EUV/Soft-X-ray region of the spectrum [16,17] and represents a promising technique to seed FEL amplifiers at shorter wavelengths. Successful experiments have been recently realized at SCSS [18] and the SPARC layout provides the additional opportunity to combine this particular seed source with an FEL undulator cascade.

In this paper, we analyze some of the proposed schemes which may be tested at SPARC. In Section 2, a brief description of the SPARC linac and undulator are, respectively, given. In Section 3, the analysis of the SPARC amplifier seeded with the harmonic generated in gas is presented in three different configurations: a single-stage amplifier (Section 3.1) the superradiant cascade (Section 3.2) and the harmonic cascade [19] (Section 3.3).

2. The SPARC FEL

The SPARC FEL is composed by a high brightness accelerator providing a high-quality beam at energies between 150 and 200 MeV (see Table 1 and Ref. [1,20]) and an undulator beam line composed by six, variable gap, undulator sections. The injector is a SLAC/BNL/UCLA 1.6 cell S-band RF photo-injector and its performances have been studied in a first phase at low energy (5–6 MeV), with a movable emittance meter. This instrument allowed the investigation of the beam parameters longitudinal evolution in the first stage of the acceleration process and has demonstrated the excellent quality of the beam at low energy [21]. The final energy is reached with three SLAC-type linac sections at 2.856 GHz whose installation has been recently completed. The first two sections are surrounded by solenoids providing additional focalization during acceleration. This solution allows beam longitudinal compression without the implementation of a magnetic chicane. It consists in exploiting a correlated velocity dispersion for obtaining the compression and the magnetic axial field properly tuned should ensure the desired emittance preservation [22]. The undulator realized by ACCEL Gmbh, is composed by six sections of 77 periods each, with a period length of 2.8 cm and a gap ranging from 6 to 25 mm. The FEL will operate in SASE mode at a wavelength of 500 nm with an

<table>
<thead>
<tr>
<th>Table 1: Summary of the main SPARC beam parameters</th>
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<tr>
<td>Beam energy: 155–200 MeV</td>
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<tr>
<td>Bunch charge: 1.1 nC</td>
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<tr>
<td>Rep. rate: 1–100 Hz</td>
</tr>
<tr>
<td>Peak current (&gt;50% bunch): 100 A</td>
</tr>
<tr>
<td>Norm emittances (integrated): 2 mm-mrad</td>
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<tr>
<td>Norm emittances (slice len. 300 μm): &lt;1 mm-mrad</td>
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<tr>
<td>Total correlated energy spread: 0.2%</td>
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<tr>
<td>Total uncorrelated energy spread: 0.06%</td>
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<tr>
<td>e-bunch duration (RMS): ~4 ps</td>
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Fig. 1. Seed injection line at SPARC.

Fig. 2. Pulse evolution in the SPARC undulator. On the left: pulse energy vs. the undulator coordinate z for the first (continuous line) and third harmonic (dashed line). On the right: pulse shape vs. time at different positions a, b and c along the undulator. The first (continuous line) and the third harmonic (dashed) are represented.
expected saturation length of about 10–12 m with the (uncompressed) beam parameters listed in Table 1.

The flexibility offered by the variable gap configuration of the SPARC undulator and the natural synchronization of the electron beam with the laser driving the photo-injector, makes the SPARC layout particularly suited for a number of experiments where the FEL amplifier is seeded by an external laser source. A seed laser chain has been installed for this purpose. The seed laser is a regenerative amplifier (LEGEND HFE by Coherent) and is driven by the same oscillator driving the photocathode amplifier.

It delivers 2.5 mJ at 800 nm with a pulse duration shorter than 120 fs. In Fig. 1 a view of the SPARC beam-line, where the main components related to the seeding experiment are visible, is shown in Ref. [23]. A gas jet interaction chamber developed at CEA is installed in the transfer line between the linac and the undulator beamline. An in vacuum optical system is used to match the transverse optical mode of the harmonic to that of the e-beam in the first undulator section [24,25]. The UV pulse is injected into the SPARC undulator by means of a periscope and a magnetic chicane deflecting the e-beam from the straight path. High-order odd harmonics of the Ti:Sa laser may be generated at the wavelengths 266, 160, and 114 nm. The undulator resonance condition is tuned at these wavelengths by varying the beam energy in the range 155–200 MeV and the undulator strength $K$.

3. Seeding experiments

3.1. SPARC as a single amplifier of HHG seed

Several simulations of the amplification of a pulse with the typical time structure of harmonics generated in gas consisting in a sequence of attosecond pulses have been done with Perseo [26]. In the example shown in Fig. 2 the SPARC FEL is seeded with the seventh harmonic of the Ti:Sa at a wavelength of 114 nm. The seed energy matched to the e-beam is 2.6 nJ. On the left the pulse energy vs. the undulator coordinate $z$ for the first (continuous...
The six SPARC undulators may be configured in order to set up a single-stage cascaded FEL based on a modulator–radiator configuration, similar to the one tested at BNL [27]. The layout of this configuration is shown in Fig. 3.

The number of sections of modulator and radiator may be adapted on the intensity of the available seed. Intense short pulses allow to test the superradiant cascade concept [13]. The seed laser power may be indeed sufficient to bring at saturation a modulator made by a single segment tuned at the seed wavelength (as in Fig. 3). The pulse generated in these conditions propagates with the typical signature of superradiance in the following radiator composed by the remaining five sections tuned at a harmonic of the seed. The feasibility of this experiment was studied in Ref. [28]. We show here that similar results may be obtained by seeding the FEL with a pulse with the time structure of HHG as in Fig. 2(a). The result of the simulation is summarized in Fig. 4, where the pulse energy along the undulator is plotted (lower left). For $z < 2.1 \text{ m}$ the energy at the fundamental (266 nm) in the modulator is shown (dashed) while for $z > 2.1 \text{ m}$ the second harmonic ($\approx 133 \text{ nm}$) is plotted (continuous). In Fig. 4(a) the pulse shape at $z = 2.1 \text{ m}$ where the fast structure from HHG is still visible, is shown. In Fig. 4(b,1) and (b,2) the pulse spectrum and shape at the end of the undulator are respectively shown. The pulse energy from the Perseo simulation exceeds 10 nJ.

3.2. FEL superradiant cascade with HHG

The last configuration considered in this analysis consists in the harmonic FEL cascade [19]. In this case the two undulators are tuned at different, non-harmonic fundamental frequencies, but have instead one of their higher-order harmonics in common. According to the SPARC FEL undulator properties, this scheme may be tested in configurations where the fourth harmonic of the 266 nm signal used as seed of the first section, is amplified as the third or fifth harmonic in the second section. This configuration has been analyzed with numerical simulations in time-dependent mode. Both the codes Perseo and a modified version of the code Genesis 1.3 [19,29], which includes the self consistent dynamics of the higher-order harmonics, were used. In the example considered in Fig. 5, we show the result obtained with Perseo, when the seed has the specific time structure of the pulse generated in gas. Seed pulses with an energy of several micro-joules have been achieved in the preliminary tests of the chambers for high harmonic generation in gas installed at SPARC [25].

In the example we assume a cascade driven by a seed of 1.5 nJ corresponding to $\sim 57 \text{ MW}$ peak power at the third harmonic of the Ti:Sa. The time structure of the seed pulse is the same as in the previous example. The first undulator has the fundamental resonance at 266 nm and the second section with $K = 1.54$ is tuned at 200 nm. The two undulators have a common resonance at 66 nm, corresponding to the fourth harmonic of the first section and the third of the second section. In Fig. 5 the evolution of the peak power vs. $z$ is shown. The energy of the radiation pulse at the end of the undulator is about 1.5 nJ. In Fig. 6 the pulse shape and spectrum are displayed.

4. Conclusions

We have given a partial overview of planned experiments constituting the scientific case of SPARC. Other schemes such as an experimental test of the fresh bunch injection technique [30] are among the capabilities of the SPARC setup and the opportunities provided by the SPARC experiment of a deeper understanding of the amplification process in a FEL together with the test of the FEL dynamics through a whole cascade, may affect the future design of foreseen FEL facilities aiming at the generation of radiation in the VUV/EUV region of the spectrum.

Acknowledgment

This work was partially supported by the EU Commission in the sixth framework programme, Contract no. 011935–EUROFEL.

References
