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Sub-picosecond coherent VUV source on the Elettra storage ring

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ABSTRACT

Taking advantage of the storage ring free electron laser beamline at Elettra, we have implemented an experimental setup for the generation of sub-picosecond (ps) coherent optical pulses in the VUV range. The setup is based on the frequency up-conversion of a high-power external signal (provided by a Ti:Sapphire laser) and makes use of a relativistic electron bunch as resonating medium. The produced VUV pulses have peak power in MW range, variable polarization, high shot to shot stability and control of the timing parameters at the ps level. In this paper, we present the first characterization of the temporal and spectral features of the emitted light. The radiation can be exploited for new experiments in the fields of dynamical phenomena, non-linear physics, magnetism and biology.

1. Introduction

The continuous efforts to improve the performance of light sources yielded in the recent past to very important achievements, such as the production of powerful coherent radiation down to wavelengths in the UV and soft X-ray ranges. However, it is only during the last decade that the development of technology allowed the transition from the conceptual design to the construction of free electron lasers (FELs) operating in the VUV-X-ray range [1–3]. This new class of machines is able to generate ultra-short pulses with extremely high brilliance, opening the possibility of exploring physical domains so far inaccessible. Most of the FEL projects under development are based on two alternative *single-pass* schemes: self-amplification of the electron beam spontaneous emission (SASE) [1–7] and coherent harmonic generation (CHG) from an input signal provided, e.g., by an external laser [8–10]. In the latter case, the amplification is driven by the input laser signal that is generally characterized by high quality spectral and temporal properties. As a consequence, one can expect a coherent and reproducible FEL output. This is not the case of SASE sources that are instead based on a stochastic emission mechanism (i.e., the electron beam spontaneous radiation) and, as a consequence, provide (longitudinally) incoherent optical pulses that present strong shot to shot fluctuations of the output power. In the standard setup for both schemes, the electron beam is supplied by a linear accelerator (linac). Modern linacs provide high quality electron bunches characterized by high peak current and low energy spread and emittance, allowing one to obtain high peak brilliance from FELs. Third generation storage rings (SRs), like Elettra, can also provide a good quality electron beam, well suited for CHG. The possibility to apply a single-pass scheme for seeded CHG in the UV spectral range has been first demonstrated at LURE [11] and more recently at the UVSOR SR [12]. In this paper, we report about the implementation of a single-pass scheme for CHG on the Elettra SR. We describe the experimental setup and present the preliminary characterization of the obtained radiation. Results show that the CHG source we have implemented may be attractive for the investigation of dynamical and non-linear phenomena.

The standard process leading to CHG using FELs is based on the frequency up-conversion of a high-power laser pulse (the so-called *seed laser*) using a relativistic electron bunch as gain medium. The process and the layout employed are sketched in Fig. 1. The laser pulse is focused into a first undulator, called modulator so as to overlap (both in space and time) an incoming electron bunch [8]. The interaction between the seed laser and the electron beam modulates the electron beam energy. Then, the beam passes through a magnetic chicane (referred in the following as the dispersive section, DS) where the energy modulation is converted into a spatial modulation of the

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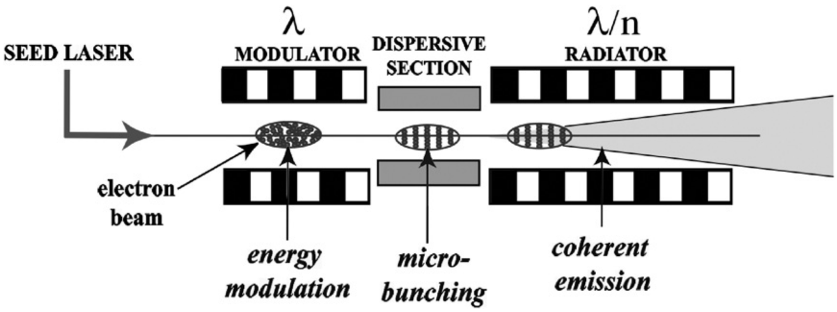

Fig. 1. Schematic layout of seeded CHG process.

longitudinal electron density into micro-bunches, with a periodicity equal to the seed wavelength. Therefore, a Fourier analysis of the bunch density shows, at the end of the DS, a series of lines at the laser frequency and its harmonics. At the exit of the DS, the beam is injected into a second undulator, called radiator, which is tuned at one of the seed harmonics. The micro-bunched electrons radiate coherently and the extracted power is proportional to the square of number of modulated electrons. If the radiator is sufficiently long, the amplification continues until saturation is reached. The radiation inherits both the properties of coherence and the temporal duration of the seed. Starting from a UV seed pulse, that can be obtained by frequency tripling of a conventional Ti:Sapphire laser amplifier, permits the generation of coherent radiation in the VUV and soft X-ray ranges, offering the possibility to overcome the ionization potential of many materials and chemical species. Combining the temporal characteristics of the harmonic pulses with techniques based on photoelectron spectroscopy could be applied in time resolved experiments with sub-picosecond (ps) resolution [13]. Moreover, shortening the wavelength improves the spatial resolution for photon scattering experiments, such as diffraction or lensless imaging techniques [14].

2. Experimental layout

The experimental setup for CHG at Elettra is based on the SR-FEL equipment [15–17]. The general layout is shown in Fig. 2. Although on a reduced scale, the scheme is equivalent to the layout designed for seeded single-pass FELs [8,18,19]. However, in this case the electron beam is re-circulated in the SR.

In the following, we describe the experimental setup, which is composed of three main blocks: the optical klystron (OK) (i.e., the suite of modulator, DS and radiator), the seed laser and the front-end station used both for the detection/diagnostics of the CHG pulses, and to focus the harmonic light into an experiment end-station. We will also report on some important issues concerning the temporal (longitudinal) and transverse alignments of the laser and electron beams.

2.1. The Elettra OK

The two APPLE-II type permanent magnet undulators, together with an electromagnetic chicane, constitute modulator (ID1), radiator (ID2) and DS of the OK (see Fig. 2a). Wavelength and polarization of the undulators are independently tunable. The emitted wavelength, λ, is determined by the following resonance condition [20]:

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right). \quad (1)$$

Here K represents the strength of the undulator and is proportional to the on-axis peak field and to the magnetic period λ_w; θ is the emission angle measured with respect to the undulator's axis and γ is the normalized electron beam energy. The previous resonance condition allows one to select the suitable resonant wavelengths for the two undulators, i.e., the seed wavelength for ID1 and the wavelength of the harmonic one wants to generate for ID2.

To maximize the coupling between the electromagnetic field and the electron bunch inside the modulator, the seed polarization must be the same as the polarization at which ID1 is set. The results presented here were obtained for linear horizontal polarization. ID2 can be set either for linear or circular polarization. This determines the polarization of the coherent emission. The DS strength is varied to optimize the micro-bunching of the electron beam. Table 1 summarizes the relevant parameters of the Elettra's OK.

In our case the radiator is not long enough to reach saturation in the CHG process. Nevertheless, as it will be shown in the following, the obtained experimental results make this setup an attractive radiation source.

2.2. The Elettra SR

Elettra is an SR dedicated to the production of synchrotron radiation and is usually operated in multi-bunch mode. It was designed to work at electron beam energies in the range 1.5–2.0 GeV. Nowadays, to satisfy the users community requests, Elettra is usually operated at 2.0 or 2.4 GeV, improving the beam lifetime and shift to higher energies the photon emission spectrum from bending magnets and insertion devices. As can be seen from Table 1, since the modulator must be tuned to the wavelength of the seed laser ($\lambda \geqslant 260$ nm, see the next paragraph), the limitation on the minimum undulator gap, restrict the values for a suitable beam energy for CHG to the range 0.75–1.5 GeV. This consideration represents the main limitation to the compatibility of CHG experiments with standard users operation, and makes necessary to allocate dedicated machine shifts for this activity.

When a seeded CHG experiment is performed, one has to take into account the potential beam instabilities that can limit or prevent the light amplification. As the output power of the CHG process depends quadratically on the number of electrons interacting with the seed multiplied by the bunching factor—the latter being proportional to the laser power—any fluctuation of the overlap between the electron beam and the laser will result in significant deterioration of the output power stability. Electron beam instabilities are particularly harmful when Elettra is operated much below 1 GeV, because at those energies the magnets' power supplies are forced to work far from their standard range. As a consequence, they provide unstable guiding fields that perturb the electron beam dynamics. A typical example