Spectral and intensity diagnostics of the SPARC free-electron-laser

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Abstract. We describe the instrument that is used for the spectral and intensity diagnostics of the SPARC free-electron-laser facility in Frascati (Italy). The instrument hosts three interchangeable gratings to cover the 50-550 nm spectral region and an EUV-enhanced CCD detector to acquire the spectrum in the single-shot operation with high resolution. The spectral resolution is in the range 2000-10000. The design, characterization and calibration of the instrument are presented and some results obtained at SPARC are discussed.

Introduction

The SPARC Free-Electron-Laser (FEL) facility is a high-brightness accelerator which provides a high-quality electron beam at energies between 110 and 180 MeV. It consists of a 1.6 cell RF injector operated in the S-band (UCLA/BNL/SLAC type, 120 MV/m). The generated beam is focused and matched into three accelerating sections (SLAC type S-band, travelling wave) to accelerate the beam up to 150 – 200 MeV [1]. The undulator beamline composed by six variable-gap modules (77 periods, period 2.8 cm, k_{max} ≈ 2.3). SPARC has been designed to test different cascaded FEL configurations in which an external light pulse generated by HHG in gas is used as the seed signal [2]. The flexibility offered by the variable-gap operating mode of the undulators and the natural synchronization between the electron beam and 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 [3-5]. Both chirped-pulse operation in the SASE mode and seeded emissions have been demonstrated at 10-Hz repetition rate. The spectral and intensity diagnostic at SPARC is performed using a normal-incidence grating spectrometer designed and realized by CNR-IFN, that is described in the following.

The instrument

The spectrometer is based on a constant deviation layout in which the selection of the spectral band acquired at the detector focal plane is made by rotating the dispersive element (i.e. the grating). In order to maintain on focus the spectral features on the detector plane, the rotation is coupled to a linear translation to adjust the distance between the grating and the detector. The whole spectral band of SPARC, that is the 50-550 nm interval, is covered by three spherical gratings (provided Newport-
Richardson Gratings, USA). The spectrum is acquired by an EUV-enhanced CCD detector (provided by Roper Scientific, USA). The layout of the instrument is shown in Fig. 1. The deviation between the entrance and the exit arms is 20 deg. The gratings are installed on a movable turret that can be rotated (for the grating selection and the spectral band tuning) and translated (for the focusing adjustment). The instrument is installed at the end of the undulators, as shown in Fig. 2. The FEL radiation is deviated to the spectrometer input by a Pt-coated plane mirror inserted after the last undulator. A filter wheel is placed in front of the entrance slit to attenuate the beam, if required. All the optical elements, i.e. the plane mirror, the filters, the gratings, and the CCD detector, have been calibrated to obtain the total absolute response of the instrument in the whole spectral range of operation. This allows the measurement of the absolute intensity of the FEL emission [3]. The main characteristics of the instrument are summarized in Table 1.

![Instrumental layout](image)

**Figure 1.** Instrumental layout: $p$ and $q$ are the input and exit arms, $\alpha$ is the deviation angle.

![Layout of the spectrometer](image)

**Figure 2.** Layout of the spectrometer connected to the FEL last undulator.

| Table 1. Instrumental parameters. |
|-----------------------------------|
| **Entrance slit aperture** | minimum 20 $\mu$m, maximum 2 mm |
| **Entrance/exit arms ($p$-$q$)** | 984 mm at zero order |
| Grating G1 | 600 gr/mm, Al-MgF$_2$ coated, 150-550 nm spectral coverage |
| Grating G2 | 1200 gr/mm, Pt coated, 100-350 nm spectral coverage |
| Grating G3 | 2400 gr/mm, Pt coated, 50-150 nm spectral coverage |
| Angular acceptance | 25 mrad $\times$ 25 mrad |
Detector

EUV-enhanced CCD, 1340 × 1340 pixel, 20-μm pixel size, 16-bit operation

Resolving element

G1 0.034 nm/pixel, G2 0.017 nm/pixel, G3 0.0084 nm/pixel

Resolution (2-pixels)

G1 2200-8100, G2 2900-10200, G3 3000-8900

Instrumental characterization

The instrument has been spectrally calibrated using as a source both a mercury lamp (in the visible and UV) and a hollow-cathode lamp (in the EUV). Some examples of the calibration spectra are presented in Fig. 3. The spectral FWHM is in the range 3 to 4 pixels for all the gratings, as expected giving the slit width of 100 μm that was used to acquire the spectra. The expected spectral resolution, calculated as the 2-pixels spectral response, ranges in the 2000 to 10000 interval. To achieve the maximum spectral resolution, the width of the entrance slit has to be set in the range 20-40 μm. The diffraction from the narrow slit assures that the footprint on the grating is large enough to illuminate a number of grooves that is sufficient to support the given resolution.

Figure 3. Spectra acquired for the spectral calibration: a) G1 600 gr/mm, λ = 546.1 nm (Hg lamp); b) G2 1200 gr/mm, λ = 73.6 and 74.4 nm (Ne hollow-cathode lamp); c) G3 2400 gr/mm, λ = 46.07 46.24 nm (Ne hollow-cathode lamp).

The responses of all the optical components, that is the mirror reflectivity, the filter transmission and the grating efficiency, were measured using the facilities available at the CNR-IFN labs in Padova. Furthermore, the CCD detector has been absolutely calibrated in the whole 50-550 nm spectral range. The calibration procedure is described in Ref. [6]. The absolute response of the spectrometer is finally shown in Fig. 4. Therefore, the spectrometer is able to provide to the users the number of photons per FEL pulse (or the energy per pulse). The latter quantity is measured by opening completely the entrance slit to let the whole FEL beam going into the instrument. In fact, the beam footprint on the slit plane is ≈1 mm in diameter, therefore at the maximum slit aperture (that is 2 mm) no photons are
blocked by the slit. In this operation mode, the spectrometer doesn’t give any detailed spectral information on the FEL emission, but only the central wavelength and the intensity. The CCD saturation is prevented, if the case, by using a suitable filter on the filter wheel.

The energy per pulse depends on the working parameters of the machine and on the FEL harmonics. As an example, a seeded emission at 400 nm gives 10 \( \mu \)J/pulse at the fundamental. The emission decreases to 1 nJ/pulse at the 7th harmonic [3]. It has been verified that the grating are not damaged at these fluence levels.

Figure 4. Absolute response of the spectrometer, expressed in CCD counts per incident photon. The Pt-coated mirror reflectivity, the grating efficiency and the detector response have been included. No filter is inserted.

Application example
The results of a seeding experiment at 266 nm are here presented as an application in which the spectrometer has been used not only as a diagnostic tool but also in the tuning phase of the machine. The seed signal is the third harmonic of a 800-nm Ti:Sa laser generated in gas. The FEL resonance has been set at the same wavelength of the seed radiation using the spectrometer as a diagnostics for the wavelength tuning. Fig. 5 shows the signal in SASE mode with the typical SASE spectral spikes (a), the seed signal of the third laser harmonic (b), and the seeded FEL spectrum (c). The peak signal of the seeded FEL is about 225 times the signal in SASE mode and about 85 times the seed signal (using a linear scale factor of 2.5 to take into account the different slit widths compared to the 1-mm beam footprint).

Figure 5. a) SASE spectrum at 266 nm, 50-\( \mu \)m slit. b) Seed spectrum at 266 nm, 50-\( \mu \)m slit. c) Seeded FEL spectrum at 266 nm, 20-\( \mu \)m slit. (courtesy of L. Giannessi)

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