FEL EXPERIMENTS AT SPARC: SEEDING WITH HARMONICS GENERATED IN GAS

L. Giannessi, A. Petralia, G. Dattoli, F. Ciocci, M. Del Franco, M. Quattromini, C. Ronsivalle, E. Sabia, I. Spassovsky, V. Surrenti ENEA C.R. Frascati, IT. D. Filippetto, G. Di Pirro, G. Gatti, M. Bellaveglia, D. Alesini, M. Castellano, E. Chiadroni, L. Cultrera, M. Ferrario, L. Ficcadenti, A. Gallo, A, Ghigo, E. Pace, B. Spataro, C. Vaccarezza, INFN-LNF, IT. A. Bacci, V. Petrillo, A.R. Rossi, L. Serafini INFN-MI, IT. M. Serluca, M. Moreno INFN-Roma I, IT. L. Poletto, F. Frassetto CNR-IFN, IT. J.V. Rau, V. Rossi Albertini ISM-CNR, IT. A. Cianchi, UN-Roma II TV, IT. A.Mostacci, M Migliorati, L. Palumbo, Università di Roma La Sapienza, IT. G. Marcus, P. Musumeci, J.Rosenzweig, UCLA, CA, USA., M. Labat, F. Briquez, M. E. Couprie, SOLEIL, FR. B. Carré, M.Bougeard, D. Garzella CEA Saclay, DSM/DRECAM, FR. G. Lambert LOA, FR. C.Vicario PSI, CH.

Abstract

The SPARC FEL has been configured to test different cascaded FEL configurations with a seed generated in gas. In the framework of the DS4 EUROFEL collaboration, a research work plan at the SPARC FEL test facility aiming at the investigation of seeded and cascaded FEL configurations was implemented [1]. The main goal of the collaboration was to study the amplification and the harmonic generation process of an input seed signal, obtained as higher order harmonics generated in gases [2,3]. We describe here the first experimental results, which were recently obtained.

INTRODUCTION

The SPARC FEL is composed by a high brightness accelerator providing a high quality beam at energies between 110 and 180 MeV [4,5] and an undulator beam line composed by six, variable gap, modules. Magnetic maps and undulator strength K vs. gap were measured before the undulator installation with a Hall probe mounted on a translation stage. These values were cross checked with the spontaneous emission spectra measured with a test electron beam, showing a good agreement [6,7]. 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. In the framework of the DS4 EUROFEL collaboration, a research work plan, aiming at the investigation of seeded and cascaded FEL configurations, was implemented [1,8]. The main goal was 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 non linear crystals and in gases. While in ref. [9] we have summarized the main results obtained with a high energy seed generated in a crystal, we report here on the seeding of the SPARC FEL amplifier with a seed generated in gas. In this paper, the first seeding experiments, exploited at SPARC and on the chirped pulse operation in the SASE mode, are described. The paper is organized as follows. In the next section the seeding system for the generation of harmonics in gas is presented, in the third section we analyse the calibrated spectrometer, which was used to determine the measured energy per pulse, and in the final section we overview the main results achieved so far.

THE SEEDING SYSTEM

The main component of the seed laser system is a regenerative amplifier (LEGEND HFE by Coherent), seeded by the same oscillator driving the photocathode amplifier. It delivers 2.5mJ at 800 nm with a pulse duration shorter than 120 fs. The laser is focused by a 2m focal length lens to an in vacuum cell, where a valve synchronized to the 10 Hz timing system of SPARC injects gas.

In Fig.1, the gas interaction chamber, developed at CEA and installed to inject radiation in the transfer line between the linac and the undulator beamline, is shown.

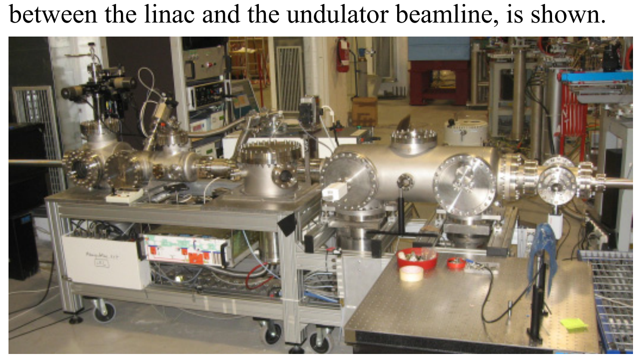

Figure 1: Harmonic generation chamber realized at CEA. The laser enters from the left side and is optically matched to the undulator by two spherical mirrors located in the chamber on the right. The differential pumping ensures vacuum at 10^{-7} mbar in the electron beamline.

The radiation seed at 266nm, as observed on a screen at about 15 m from the source, is shown in Fig.2. While the radiation transverse intensity showed a reasonably regular profile (Fig. 2), the spectrum of the seed presented a double peak structure, as shown in Fig.3.

Figure 2: Spot of the 266nm radiation seed generated in gas as observed on a screen at about 15 m from the interaction point.

The spectrum at 266nm was registered by the spectrometer at the end of the undulator. The energy on higher order harmonics (160nm and 114nm) was not sufficient to detect a signal above the camera background noise. The double peak structure was observed only during this shift, and was not registered on the IR laser radiation before conversion at 800 nm. These preliminary experiments were performed with the double peak structure in the spectrum.

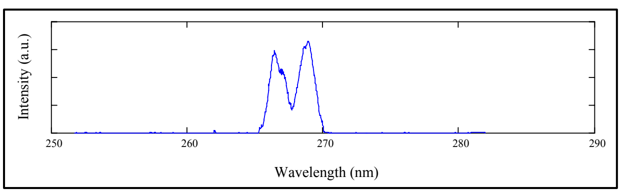

Figure 3: Seed spectrum at 266 nm.

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 [1]. 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 266nm, 160nm, and 114nm.

THE SPECTROMETER AND ABSOLUTE PULSE ENERGY MEASUREMENT

In order to evaluate the total energy from any acquired spectrum we must take into account the correction factors due to several optical elements, which affect the radiation properties after it exits from the last SPARC undulator module. A layout of the present setup is shown in Fig.4.

Last mirror reflectivity - In the 6th diagnostic chamber, after the exit from the last undulator, a platinum coated mirror drives the light beam towards the spectrometer. Reflectivity was measured with un-polarized light below 200nm (red dots in Fig.5) The FEL radiation is *P* polarized and the theoretical P reflectivity has been used in deriving the calibration factor.

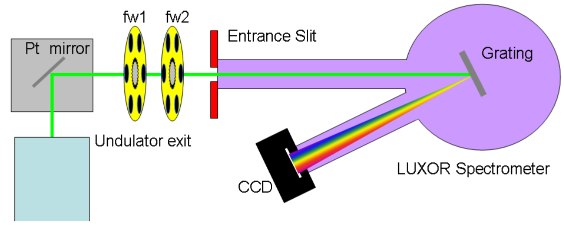

Figure 4: Layout of the SPARC optical elements from the undulator exit to the CCD camera of the spectrometer.

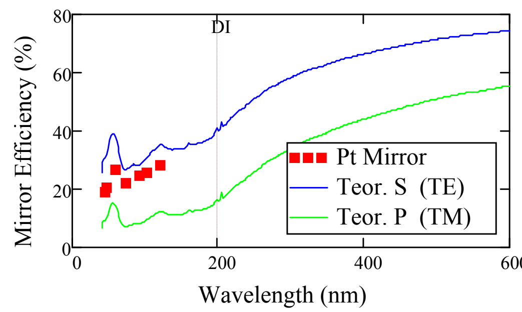

Figure 5: Efficiency of the platinum mirror in the 6th diagnostic chamber.

Filters - Some different filters are available along the radiation beam line, mounted on two filter-wheels (FW1,FW2). The filters are of two different types, neutral density (NDF) and narrow bandwidth (N-bw) (Table 1). The neutral density filters allow to attenuate the intensity of the signal on the CCD, and they can be used at a wavelength higher than 350nm. The narrow bandwidth filters are used to remove intense signals from long wavelengths while observing the higher order harmonics of the FEL or the seed laser.

Table 1: Available Filters at SPARC

FW1	**Tr.**	**FW2**	**Tr.**
NDF >350 nm	0.33	N-bw @ 120nm	0.2
NDF >350 nm	0.1	N-bw @ 160nm	0.2
NDF >350 nm	0.01	N-bw @ 266nm	0.17
NDF >350 nm	0.001	Al 250nm <60nm	0.2
NDF >350 nm	0.0001		

Entrance Slit Calibration - At the entrance of the spectrometer the light passes through a rectangular slit of variable horizontal width (30-2000 μm). The slit do not affect the beam vertical size. Assuming a circular beam, we recover the energy lost at the slit as a function of its width. In the vertical direction we detect the spot profile and by imposing circular symmetry, we reconstruct the spot intensity before the slit. By reconstructing the image of a fixed source for different slit widths, we derived the slit calibration curves (Fig.6). This procedure was checked by using as source the SASE FEL radiation (500 nm) and the seed laser (400 nm), and similar results were obtained.

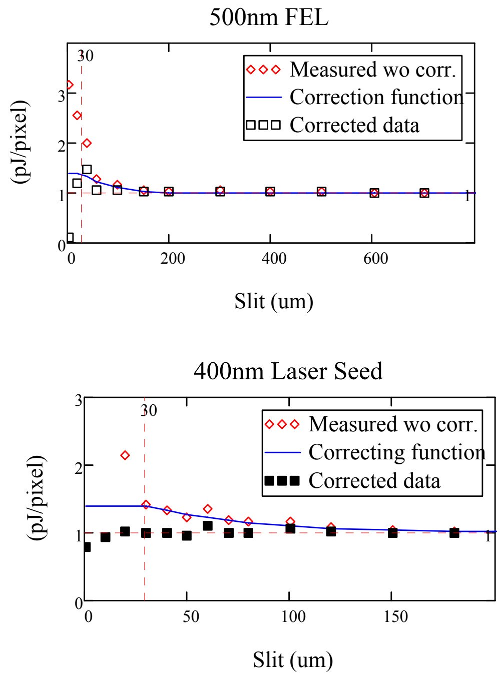

Figure 6: Entrance slit calibration curve.

Spectrometer Efficiency - Three different gratings are available: 600, 1200, and 2400 gr/mm. The first two are Al/MgF_2 coated, the last is Pt coated. Each one is characterized by its own efficiency curve in the frequency range listed in Tab. 2. The spectrometer is provided by a CCD detector with a gain value of 1.14 e-/ADU (analog to digital unit). The CCD efficiency (e-/incident ph) is given by the product of the quantum efficiency (interacting ph/incident ph) and the quantum yield (e-/ph interacting).

Table 2: Spectrometer: Gratings and CCD specifications

Grating (gr/mm)	Available Wavelength	Wavelength Window	CCD Resolution
G600	250-600 nm	45.56 nm	0.034 nm/pix
G1200	46-546 nm	23.316 nm	0.017 nm/pix
G2400	46-160 nm	11.658 nm	0.0087 nm/pix

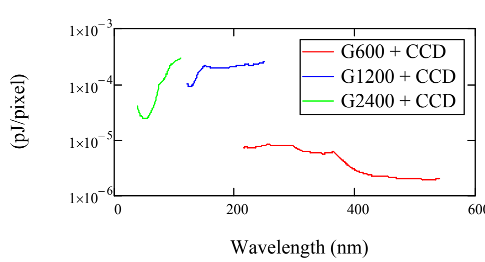

Figure 7: Spectrometer total efficiency curve.

The spectrometer efficiency is given by the product of the grating efficiency and the CCD efficiency (Fig.7). We have taken into account the presence of an optic camera, which zooms on the CCD the image of the entrance slit with a magnification factor of 1.374.

Global Calibration - The global calibration (Fig.8) is the product of the calibration curves of all the elements crossed by the light at a given wavelength: last mirror, filters, grating, CCD.

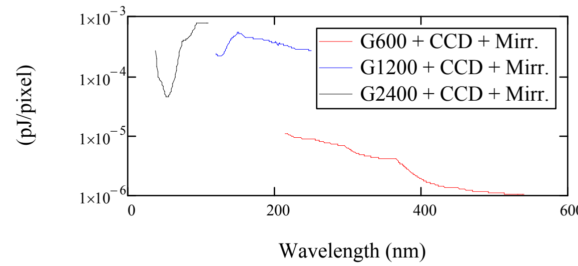

Figure 8: Global Calibration curve calculated without filters.

The calibration procedure was tested at 500nm by comparing the energy reconstructed from the SASE spectra with the direct measurement from a calibrated high sensitivity pyroelectric detector The data have been obtained at different pulse energies by varying the number of undulator modules (green dots on the right scale of Fig.9)

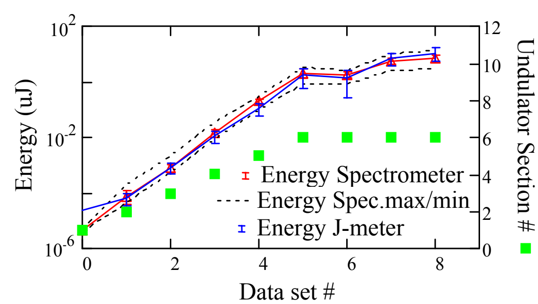

Figure 9: Comparison of energy measured with pyroelectric detector and reconstructed from the spectrum. Error bars (red) correspond to one standard deviation over 100 shots.

SEEDING WITH HARMONICS GENERATED IN GAS

The FEL amplifier has been seeded with the radiation generated in a gas cell at 266nm (spectrum in Fig.3). The seed energy was about 50 nJ. After ensuring a transverse spatial overlap in the first undulator module, we have scanned the seed delay to ensure a proper synchronization between electrons and radiation. The output energy vs. delay is plotted in Fig. 10 together with the e-beam current, measured with the RF-Deflector at the entrance of the undulator. An arbitrary delay has been added to the trace to superimpose the two curves. A large energy jitter was the main reason of the large standard deviation observed in the figure. The corresponding linewidth is shown in Fig. 11. The SPARC undulator may be operated as an undulator cascade, where the first modules are tuned at the seed wavelength 266nm in this case, and the last modules are tuned at the second harmonic (133nm). We have explored this configuration varying the number of modulators/radiators (with six total modules). The optimized number of undulator modules operating as radiator and modulator depends on the input seed energy. The higher output energy E=1μJ at 133nm was obtained with four undulators as modulators and two radiators (Fig.12). A typical spectrum, obtained in single shot mode in this configuration, is shown in Fig. 13.

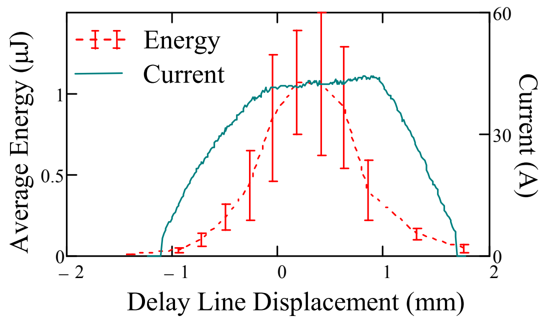

Figure 10: Average energy (± 1 std. dev.) from the seeded FEL compared to the e-bunch current measured via RF deflector.

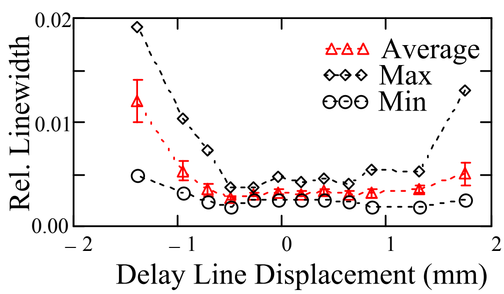

Figure 11: Relative linewidth vs. delay line displacement.

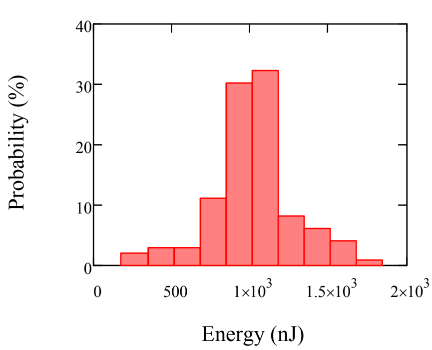

Figure 12: Histogram of the output pulse energy at 133nm in a sequence of 100 shots.

CONCLUSIONS

The measure of the pulse energy in the UV/VUV spectral range may be obtained from the analysis of the CCD images resulting from in vacuum spectra acquisitions. Applying this method, information can be gained from the single shot spectra acquisitions, such as energy, bandwidth, central wavelength, spot size (vertical). These quantities can be correlated with structures or other details, which can be observed in the 2D (spectral/position) images, such as the one shown in Fig.13.

Furthermore, we have presented the preliminary results obtained by seeding the SPARC free electron laser with harmonics generated in gas. Experiments at 266nm ensured the possibility of easily finding the spatial superposition and the synchronization between electrons and seed. Preliminary tests at 160 nm have shown amplification of the seed signal and will be the subject of forthcoming investigations.

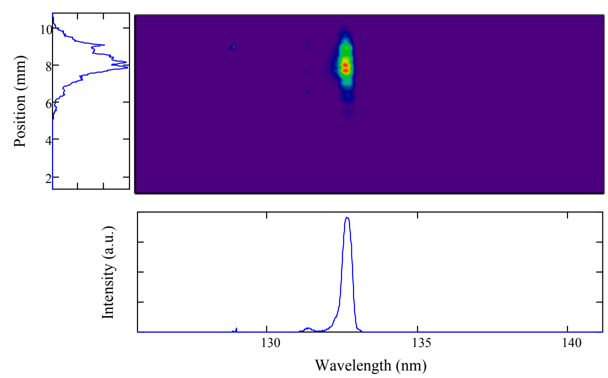

Figure 13: Single shot spectrum of the FEL cascade seeded with radiation at 266nm generated in gas. The horizontal axis represent the wavelength, the vertical axis represents the position at the spectrometer slit.

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