SEEDING THE FEL OF THE SCSS TEST ACCELERATOR WITH THE 5TH HARMONIC OF A TI: SA LASER PRODUCED IN GAS

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Abstract

Today, single-pass Free-Electron Lasers (FEL) produced a highly bright radiation, the Self Amplified Spontaneous Emission (SASE), which spectral and temporal profiles are composed of a series of spikes. We demonstrate here the strong and *coherent amplification* of the 5th harmonic of a Ti: Sa laser (800 nm, 10 Hz, 100 fs) generated in a gas cell, i.e. 160 nm, by the SCSS (SPring-8 Compact SASE Source, Japan) Test Accelerator FEL. This is obtained by overlapping transversally, spectrally and temporally the external harmonic source in the in-vacuum undulator with the electron beam (150 MeV, 10 Hz, 1 ps). With only one undulator section, the 160 nm seeded emission achieves *three orders of magnitude* higher intensity than the unseeded one, and presents a quasi perfect Gaussian shape in the spectral distribution. This spectacular phenomenon is associated to the generation of intense and coherent Non Linear Harmonics (NLH) at 54 nm and 32 nm. Finally, in view of the *low seed level required*, such amplification associated to NLH schemes would allow the generation of fully coherent soft X-ray radiations down to the "water window".

INTRODUCTION

Nowadays, most of the new FEL sources are dedicated to the Self Amplified Spontaneous Emission (SASE) [1]-[2], which provides with a very high brightness photon beam at short wavelength but with limited temporal coherence. In 2000, a seeded FEL at 1.06 µm combined to the generation of coherent harmonics has been demonstrated experimentally [3]. It has been established that the seeded beam gave its full coherence property to the emitted radiation and allowed to decrease the saturation length in a more compact source. Also, injection of a single-pass FEL by the 3rd laser harmonic of a Ti:Sapphire laser from crystals (266 nm, 4 µJ, 5 ps FWHM) led to large amplification [4]. Seeding a FEL with high-order laser harmonics generated in gas (HHG), which present high degrees of spatial and temporal coherence [5], offers an extension to short wavelength. Indeed, HHG sources with appropriate peak power now exist down to the water window [6]-[7]. Consequently, seeding a FEL becomes pertinent for generating intense and fully coherent short wavelength radiation.

These last years, a few FEL proposals, like ARC-EN-CIEL (Accelerator Radiation Complex for Enhanced Coherent Intense Extended Light) [8], have adopted this configuration as the main operation mode and FEL facilities based on SASE emission have even decided to implement it, like the SCSS (SPring-8 Compact SASE Source, Japan) Test Accelerator [9]-[11], the SPARC (Sorgente Pulsata e Amplificata di Radiazione Coerente) source [12] and FLASH (Free-electron LASer in Hamburg) [2].

GENERAL PRESENTATION

The seeding experiment has been carried out on the FEL of the SCSS Test Accelerator [13]-[14]. This facility is mainly based on a thermionic cathode electron gun (1 nC), a C-band LINAC (5712 MHz, 35 MV/m) and an in-vacuum undulator (15 mm of period, 2 sections of 4.5 m length). In June 2006, the first lasing has been observed at 49 nm [15] and the full saturation has been reached in 2007. From the HHG part, the experiment has been designed and tested in France in 2005 and finally implemented (Figure 1) inside the accelerator tunnel of the SCSS area in 2006.

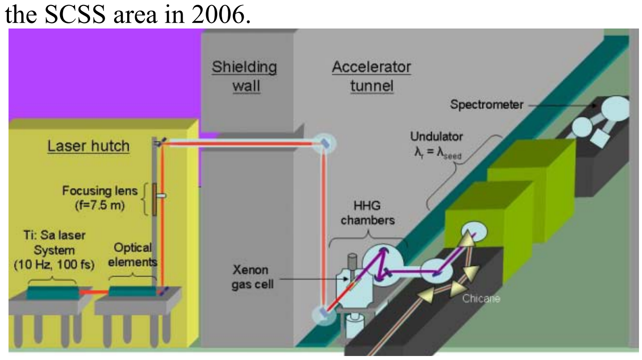

Figure 1: General layout of the seeding experiment with harmonics generated in a gas cell.

The laser system, used for generating the HHG light, is based on a Chirped Pulsed Amplification (CPA) Ti: Sa technology, and is mainly composed of a Tsunami mode-locked oscillator, a Spitfire regenerative chirped-pulse amplifier and a Coherent multipass amplifier. It delivers a high energy IR laser beam (50 mJ, 10 Hz, 100 fs). This latter is focalized by a lens of 7.5 m focal length in a cell filled with Xe gas, which is a well-adapted gas for the generation of the 160 nm radiation. As the Ti: Sa laser system is installed outside the tunnel of the accelerator and in order to pass through the shielding wall (2.3 m of height for radiation safety reasons), the IR beam is propagated on two IR periscope systems helping for performing the alignment in the gas cell, located in the first chamber of the harmonic generation experiment.

The second chamber contains the VUV telescope and periscope systems. They allow the generated 5th harmonic to be efficiently propagated, and refocalized into the first undulator section, taking advantage of the magnetic chicane, in order to adapt its divergence as closed as possible to the electron beam one. Also, both beams have to be precisely transversally overlapped (Figure 2) all along the entire undulator and synchronized (Figure 3) with subfemtosecond precision.

GENERATION OF HIGH ENERGY SEED

For optimizing the harmonic generation process, the IR laser beam properties have to be adjusted. Using an afocal system, the diameter of the multipass amplifier beam is doubled, for decreasing the power density on the propagation mirrors and in opposite to have a shorter waist in the gas cell and consequently a higher power density for the generation process. A final iris allows the geometry and the density profile of the beam to be finely changed. With those systems, the energy is reduced roughly to 20 mJ in a 20 mm full diameter.

The polarization of the IR beam, which is originally horizontal, has been switched twice during the transport over the concrete wall to be retransformed into horizontal one. Indeed, as the harmonic beam presents the same polarization as the IR beam, it enters with a horizontal electric field inside the first undulator section, especially designed for amplification in this polarization.

Finally, the gas pressure, entering the gas cell, is regulated by changing the aperture of an up-stream micro-leak valve, placed outside the accelerator. The gas pressure evolution can be followed by reading a calibrated pressure detector directly located after the micro-leak valve.

OPTICAL ALIGNMENT

It is needed that the seeded radiation be co-propagated with the electron beam for having a good overlap inside the first undulator. As the harmonics are collinear to the IR laser, which is intense and reflected by the OTR screens, one should align the electron and IR laser beams. In order to focus the harmonic beam at various positions inside the first undulator section, a translation stage has been added below the second spherical mirror of the VUV telescope. The alignment is performed with OTR (Optical Transition Radiation) screens, which are disposed on the electron and IR beams way at entrance and exit of each undulator section. By looking at the corresponded CCD camera screens (Figure 2) and adjusting the angles of the two flat mirrors of the VUV periscope, the two beams are superposed.

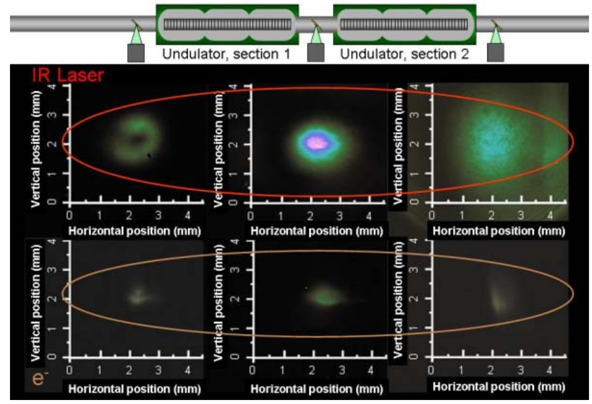

Figure 2: CCD pictures of the IR and electron beams OTR emissions for aligning the harmonics on the undulator emission axis.

SYNCHRONIZATION

The synchronization between the electron beam and the seed pulse is achieved by locking the Ti:Sapphire oscillator to the highly stable 476 MHz clock of the accelerator. The timing is then adjusted with a few ps resolution using a femtosecond streak camera (Hamamatsu Photonics FESCA-200-C6138), on which the IR laser light and the OTR emission from the electron beam are injected (Figure 3 a and b). Finally, a motorized fine optical delay line, installed on the IR laser path, allows reaching fs level temporal overlap between the IR laser and the electron beam (Figure 3 c).

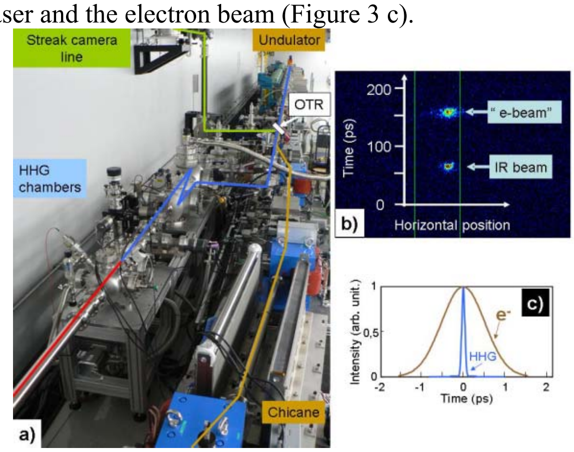

Figure 3: a) Inside view of the accelerator tunnel: HHG experiments, magnetic chicane, undulator and streak camera line. b) Streak camera picture for ps synchronisation. c) Theoretical temporal overlap after moving the optical delay line.

RESULTS

The amplification of the seed occurs through the two undulator sections, separated by a 1.5 m length drift space and the final radiation is observed on the CCD camera of a dispersive spectrometer. As the photon beam is dispersed horizontally by the grating, the CCD camera reveals pictures (Figure 5), in which the vertical axis is the vertical position of the beam and the horizontal axis is the wavelength. When the seed is well aligned and spectrally matched with the undulator emission axis, the FEL seeded radiation is highly amplified even with only one undulator section and with a seed of 0.53 nJ energy per pulse (40 fs FWHM). The spectral emission presents regular quasi perfect Gaussian shape pulse to pulse, slightly red-shifted compared to the normal radiation. This effect is due to the additional exchange of energy with the ebeam. The spatial shape seems to be similar to the unseeded emission, meaning that the good spatial coherence of the FEL is at least kept similar. The energy reached by the FEL is estimated to be about 300 nJ.

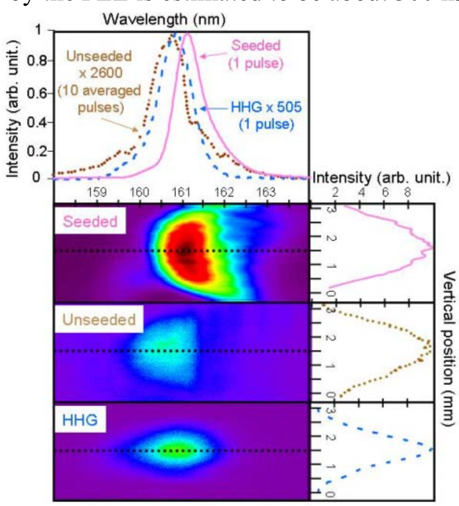

Figure 4: Comparison between the FEL seeded emission, the unseeded emission and the HHG seed at the fundamental emission wavelength (160 nm). The seed pulse energy was 0.53 nJ and only the first undulator section was used for amplifying the HHG pulse.

This amplification is accompanied by the generation of coherent FEL non linear harmonics, and more particularly the 3rd and 5th ones (Figure 5), respectively at 54 nm (~300 pJ, ~40 fs FWHM) and 32 nm (~10 pJ, ~40 fs FWHM), while the energy of the electron beam is only here of 150 MeV. The NLH show similar spectral behaviours than the fundamental.

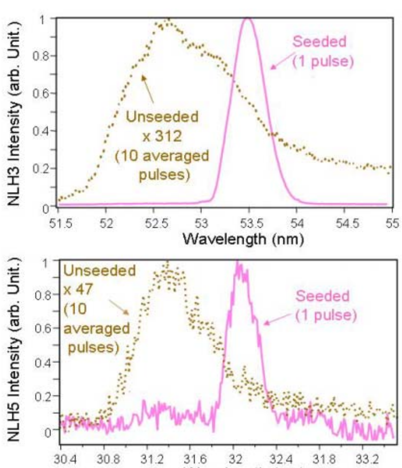

Figure 5: Spectra of the 3rd and 5th NLH. The seed pulse energy was 0.53 nJ and only the first undulator section was used for amplifying the HHG pulse.

Taking into account the pulse duration difference between the unseeded emission (~1 ps) and the seeded one, for the fundamental and also for NLH, the measured spectral widths indicate that the temporal coherence is largely improved with the seed injection.

CONCLUSIONS

We showed here, for the first time, the strong enhancement of a harmonic source generated in gas at 160 nm on the SCSS test accelerator FEL, while using only a single undulator section. In this case, the pulses are coherently amplified. They present a distribution almost Gaussian, with an intensity of three orders of superior magnitude to the one obtained without injection.

Seeding a FEL with HHG radiations offers a real timeliness to spread the spectral range of the FEL towards the short wavelengths. In fact, these days, some table-top laser installations of harmonic generation produce pulses to the water window with notable peak powers. Also, in the view of the weak injection level required here (<0.5 nJ) and the strong factor of amplification attained, it is reasonable to envision to realize in a short time a FEL, at a relatively low energy, allowing generating intense and totally coherent radiations at a wavelength around the nanometre.

Besides, the generation system already allows to generate harmonic in the plateau region, i.e. from 70 nm to 30 nm, and with a level of comparable energy to the one used here. Also, an immediate extension of this scheme to 60 nm is foreseen for 2008-2009.

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