FEL EMISSIONS AT 160 NM IN SEEDED CONFIGURATION ON THE SCSS TEST ACCELERATOR

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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 have demonstrated 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. With two undulator sections, the seeded FEL spectrum reveals first effects of saturation.

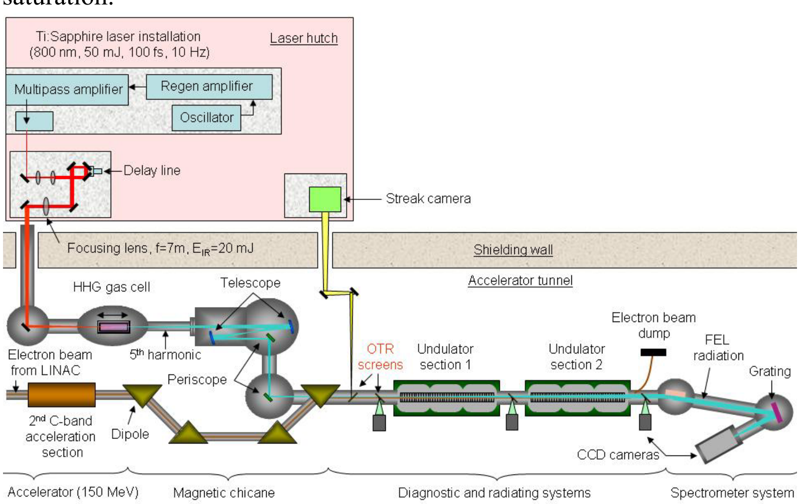

Figure 1: General layout of the seeding experiment with harmonics generated in a gas cell. A Ti:Sapphire laser (800 nm, 20 mJ, 100 fs FWHM, 10 Hz) is loosely focused into a xenon gas cell (focal length f = 7 m), optimizing HHG output. Using the telescope (SiC mirrors) and periscope optics (CaF_2 mirrors), the HHG seed beam is spectrally selected, refocused, spatially and temporally overlapped with the electron beam (150 MeV, 1 ps FWHM, 10 Hz) in the two consecutive undulator sections 1 and 2, which are both tuned to 160 nm corresponding to the 5th harmonic of the laser. Beam position is monitored on OTR (Optical Transition Radiation) screens.

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 (Figure 1) 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.

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 (20 mJ, 10 Hz, 100 fs), which is focalized by a lens of 7.5 m focal length in a cell filled with Xe gas, a well-adapted gas for the generation of the 160 nm radiation.

Then, the VUV telescope and periscope systems 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 the HHG divergence as closed as possible to the electron beam one. Also, both beams have to be precisely transversally overlapped all along the entire undulator and synchronized (Figure 2 and Figure 3) with subfemtosecond precision.

SPATIAL AND TEMPORAL OVERLAPPING

It is needed that the seed radiation be co-propagated with the electron beam for having a good overlap inside the first undulator section. The alignment is performed with OTR (Optical Transition Radiation) screens, which are disposed on the electron beam way at entrance and exit of each undulator section. Actually, 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. 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. Finally, 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.

In the meantime, the synchronization between the electron beam and the seed pulse is achieved by locking the Ti:Sapphire oscillator to the highly stable 240 MHz clock of the accelerator (Figure 2).

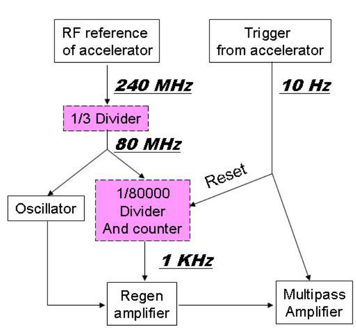

Figure 2: scheme of the synchronization system between each IR laser facility part and the accelerator.

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).

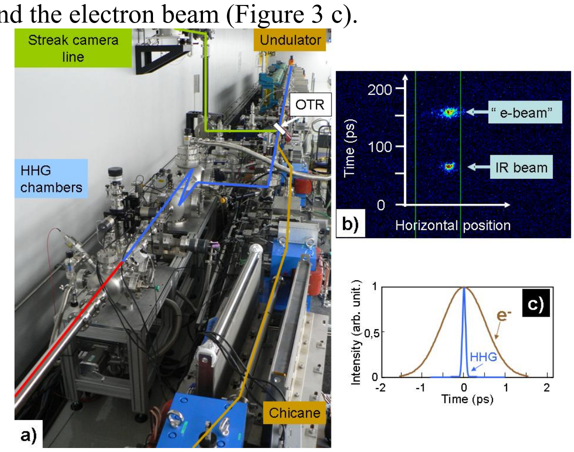

Figure 3: a) Inside view of the accelerator tunnel: HHG experiments, magnetic chicane, undulator and streak camera line. b) Streak camera picture for ps synchronisation. c) Theoretical temporal overlap after moving the optical delay line.

RESULTS

The amplification of the seed can occur through the two undulator sections if needed, 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 4), in which the vertical axis is the vertical position of the beam and the horizontal axis is the wavelength of emission.

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 unseeded and HHG radiations. 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. In those conditions, the energy reached by the FEL is estimated to be about 300 nJ.

Once both undulator segments are set in resonance with the seed wavelength, the spectral distribution exhibits a sideband structure (Figure 5). This probably indicates an over-bunching of the electrons performing synchrotron oscillations after saturation [16]. The spectral red-shift approximately reaches twice larger values (~2.5) compared with the single undulator case, demonstrating additional energy transfer from the electron beam to the FEL field.

Finally, taking into account the pulse duration difference between the unseeded emission (~1 ps) and the seeded one, with one or two undulator sections, the spectral widths indicate that the temporal coherence is largely improved with the seed injection.

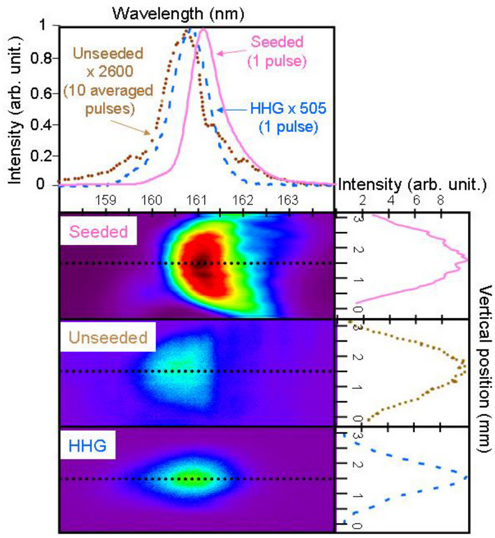

Figure 4: Comparison between the FEL seeded emission, the unseeded emission and the HHG seed at the fundamental wavelength (160 nm). The 1D-spatial (vertical) and spectral distributions are mapped on the CCD camera of a spectrometer; spatial (right) and spectral (up) profiles are plotted at maximum intensity. The lines correspond to the seeded (single shot, ——), unseeded emission (averaged on 10 shots, — ·), and the HHG seed (single shot, •••). The seed pulse energy was 0.53 nJ and only the first undulator section was used for amplifying the HHG pulse.

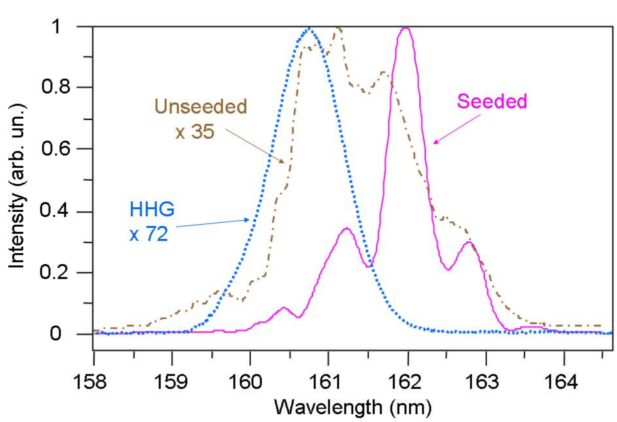

Figure 5: Spectra of the FEL fundamental emission using the two undulator sections: unseeded (single shot, — ·) and seeded (single shot, ——) obtained with a 4.3 nJ seed (single shot, •••). The FEL gain is smaller compared with the measurements of Figure 5, because of lower electron beam brightness, transverse misalignment and spectral detuning ($\lambda_{Seed}-\lambda_{unseeded}\leq 0$).

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 and present a distribution almost Gaussian, with an intensity of three orders of superior magnitude to the one obtained without injection. The adding of the second undulator section allows first effects of saturation of the FEL light to be observed.

Seeding a FEL with HHG radiations offers a real opportunity to spread the spectral range of the fully coherent FEL towards short wavelengths. In fact, these days, some table-top laser installations of harmonic generation produce radiations close to the water window and 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 imagine to realize in a short time a FEL, at a relatively low energy, allowing generating intense and totally coherent radiations at a nanometre scale wavelength.

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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