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Generation of Fourier-limited pulses in the XUV with seeded FELs

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The advent of lasers revolutionised experimental physics, enabling scientists to utilise coherence to access new states of matter and develop innovative techniques. The recent development of Free Electron Lasers (FELs) extends many laser properties—such as ultra short pulses, transverse coherence, and high intensity—into the X-ray spectral range, marking the beginning of a new scientific era. The ability to generate fully coherent FEL pulses has opened opportunities for advanced techniques, including coherent control at much shorter wavelengths. Achieving complete control of electromagnetic fields via FELs requires precise manipulation of the underlying physical processes. Employing an external seed to initiate FEL amplification has proven to be a promising approach for producing fully coherent pulses. However, this method demands significant effort in controlling the electron beam properties responsible for FEL amplification.

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Keywords: Free Electron Laser, X-ray laser, coherent FEL.

1 Introduction

The development of sources based on relativistic electron beams, such as Free Electron Lasers (FELs), has provided effective methods for generating powerful radiation across a broad spectral range, from the far-infrared to hard X-rays [1]. The fundamental concept of 10 FELs, involving radiation amplification via stimulated emission from relativistic electrons in a periodic magnetic field, was proposed by Madey [2] a few years after the first demonstration of laser emission [3], with the goal of extending laser capabilities into a wider spectral domain. Following the initial experimental demonstration of FEL amplification [4], FELs have been widely utilised to generate high-power infrared and visible radiation [5,6].

It was only towards the end of the 20th century that rapid advancements in accelerator technology enabled the production of high-quality electron beams suitable for FEL operation at shorter wavelengths, marking the beginning of the X-ray FEL era [7,8]. Today, several user facilities provide intense radiation down to the Angström wavelength range, delivering pulses as short as sub-femtoseconds and with peak powers approaching the terawatt (TW) level [9-14]. The unique radiation properties available at FEL facilities have driven the development of novel experimental techniques, leading to significant scientific breakthroughs [15].

Although X-ray FEL pulses share many characteristics with short pulses produced by 24 modern optical lasers, the dominant generation mechanism in most current FELs—Self Amplified Spontaneous Emission (SASE) [16,17]—typically does not yield pulses with a high degree of longitudinal coherence [18]. While the stochastic nature of SASE radiation is not a barrier for many experimental applications, it can limit techniques that depend critically on full temporal coherence.

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In the X-ray spectral region, where optical cavities are not viable, alternative approaches have been developed to produce coherent FEL pulses by seeding the amplification process with an external coherent source [19]. Among the various techniques, one of the most effective for controlling the FEL coherence properties involves initiating the FEL process with an external laser and amplifying one of its harmonics. The FERMI FEL facility [11] was specifically designed based on the High-Gain Harmonic Generation (HGHG) seeding scheme [20], enabling coherent light production over a spectral range from 100 nm down to 4 nm [21,22].

The availability of high-coherence pulses in the extreme ultraviolet (XUV) regime, exhibiting properties comparable to those typically achievable with standard optical lasers [23], has recently driven significant progress in the fields of quantum coherence and coherence control within the vacuum ultraviolet (VUV) and XUV spectral ranges [24-28]. The significant opportunities offered by this coherence and the capability to generate Fourier-limited pulses at FELs have increased attention on understanding and controlling the underlying mechanisms, necessitating careful design and optimisation of FELs to meet these demands. The major interest in these opportunities is also demonstrated by the increasing number of FEL facilities aiming to implement external seeding to produce coherent pulses [29-31].

In this work, we present recent advancements in this field, with particular emphasis on the FERMI FEL, highlighting critical aspects of seeded FEL operation that influence the ability to produce fully coherent pulses. After a brief overview of the HGHG scheme, we discuss how electron beam properties impact the final FEL pulse characteristics and examine the methods employed to mitigate these effects.

2 Externally Seeded FEL: High-Gain Harmonic Generation

To overcome the limitations of SASE, externally seeded FELs have been proposed as a viable solution for coherent sources at wavelengths where optical cavities are not feasible. The core principle of external seeding is to imprint the desired coherence properties of a well characterised, conventional laser (the ”seed” laser) onto the high-energy electron beam. This imprinting process ensures that the subsequent FEL emission exhibits significantly improved temporal coherence, spectral purity, and stability. Furthermore, external seeding allows for precise control over the FEL pulse properties, including its central wavelength, bandwidth, and temporal shape, opening new avenues for sophisticated scientific investigations.

Several schemes for external seeding have been proposed and implemented. Among these, HGHG [32] has emerged as a particularly successful and widely adopted technique, especially for generating coherent radiation in the VUV and soft X-ray regions [20,33].

The HGHG scheme is a multi-stage process that efficiently up-converts the frequency of a conventional seed laser to much shorter wavelengths. A typical HGHG FEL consists of three main sections (Fig 1):

• **Modulator:** In this section, the relativistic electron beam co-propagates with the external seed laser pulse. The resonant interaction between the electrons and the seed laser field leads to a periodic energy modulation of the electron beam at the wavelength of the seed laser (Fig 1b). The strength of this modulation is carefully controlled to optimise the subsequent bunching process.

• **Dispersive Section (or Chicane):** Following the modulator, the energy-modulated electron beam passes through a dispersive section, typically a magnetic chicane. This section translates the energy modulation into a spatial (density) modulation. Electrons with higher energy travel a shorter path through the chicane, while lower-energy electrons take a longer path. This differential path length causes the electrons to bunch together, forming microbunches separated by the seed laser wavelength (Fig 1c). Critically, these microbunches contain significant harmonic content of the initial seed laser frequency.

• **Radiator:** The periodically bunched electron beam then enters a second, longer undulator section called the radiator. This undulator is typically tuned to resonate at a high harmonic of the initial seed laser frequency.

As the microbunched beam traverses the radiator, it emits coherent radiation at this selected harmonic wavelength. The intensity of the emitted radiation grows exponentially along the radiator due to the coherent superposition of fields from the densely packed electrons within each microbunch (Fig 1d).

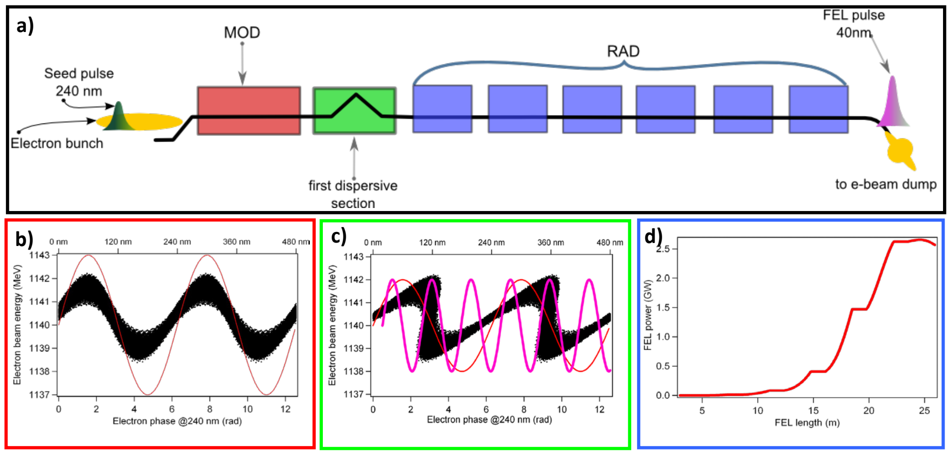

Fig 1. Schematic steps of HGHG. (a) Electron bunch (yellow) and laser pulse (green) are overlapped in a dedicated beamline section composed of a modulator (MOD), a dispersive section, and a long radiator (RAD). (b) The electron beam phase space is energy modulated in the modulator. (c) The dispersion converts energy modulation into density modulation. (d) Finally, the beam emits coherently, and FEL radiation is exponentially amplified to saturation in the radiator.

The seed laser quality is crucial, as it imprints the phase on the electron beam that is subsequently transferred to the emitted FEL radiation, enabling coherent pulse generation. However, a uniform electron-beam phase space is equally essential to preserve this laser-induced coherence.

3 FERMI

The FERMI Free Electron Laser (FEL) [11] at the Elettra Sincrotrone Trieste laboratory in Italy is a cutting-edge user facility delivering high-brightness, ultrashort pulses of coherent radiation in the extreme ultraviolet (XUV) to soft X-ray spectral range. A key distinguishing feature of FERMI is its seeded operation mode. FERMI utilizes an external laser to impose initial coherence on the electron bunches. This ”seeding” process, based on HGHG, results in FEL pulses with exceptional properties (Fig 2): high stability in wavelength and intensity, narrow spectral bandwidth (close to the Fourier limit) [34], and precise synchronisation capabilities with external lasers [35], making it ideal for time-resolved pump-probe experiments.

FERMI currently operates two FEL lines, FEL-1 [21] and FEL-2 [22], which cover complementary spectral regions and offer tunable polarization (linear and circular) [36]. FEL-1 typically covers the lower energy range, from approximately 12 eV to 65 eV (100 nm to 20 nm), employing a single-stage HGHG scheme. FEL-2 extends to higher photon energies, roughly from 65 eV up to 310 eV (20 nm to 4 nm), utilizing a double-stage HGHG cascade with a “fresh bunch” injection technique in the second stage to reach shorter wavelengths.

The facility’s unique characteristics enable a wide array of advanced experimental techniques, including time-resolved spectroscopy, coherent diffraction imaging, and studies of non-linear phenomena in matter. Continuous upgrades and development efforts, such as the implementation of Echo-Enabled Harmonic Generation (EEHG) schemes [37], aim to further extend FERMI’s spectral reach and enhance its performance, opening new frontiers in ultrafast science.

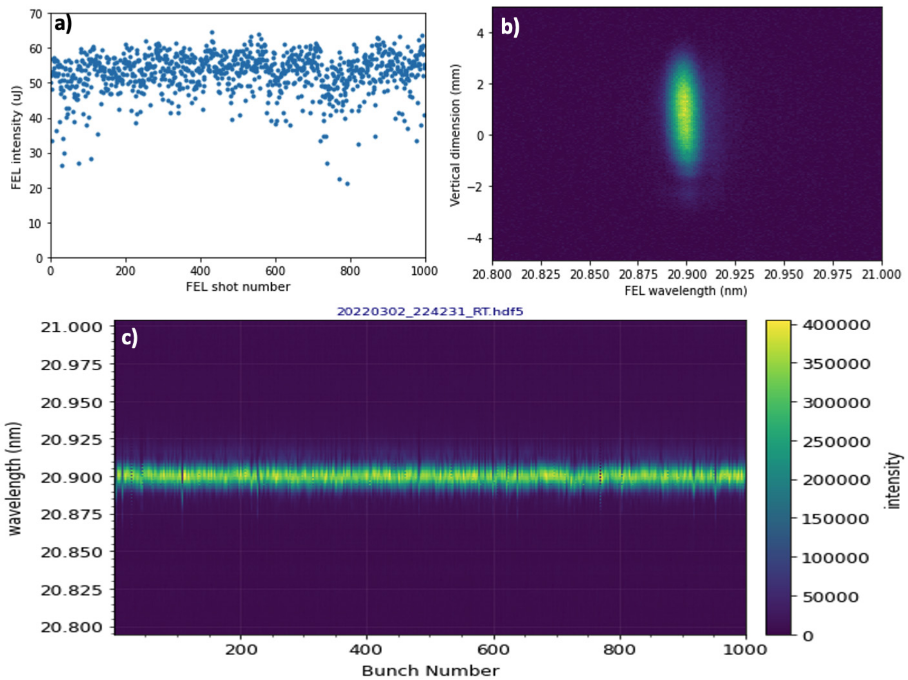

Fig 2. Typical FEL performance of FERMI FEL-1. (a) Trend of FEL pulse energy and (c) spectra for 1000 consecutive shots; (b) typical FEL spectrum as measured with the online spectrometer.

A. Electron beam

Generation of gigawatt (GW) level pulses in the XUV and soft X-ray spectral range calls for electron beams characterized by high brightness [38]. Typical electron beam parameters for FELs in this spectral range, and for FERMI, are listed in Table 1.

Table 1. Typical range for electron beam parameters in the XUV/soft X-ray spectral range; FERMI nominal values in brackets.

Parameters	Value	
Charge	100 – 500 (500)	pC
Peak current	500 – 1500 (700)	A
Slice emittance	0.2 – 1.0 (0.7)	mm·mrad
Energy	1.0 – 3.0 (1.5)	GeV
Slice energy spread	50 – 1000 (150)	keV
Beam size	50 – 100 (75)	µm

Generating electron beams with these characteristics requires powerful accelerators, combined with complex beam-manipulation systems that compress the bunches to the required peak current once they reach a relativistic energy [39].

While high beam brightness is essential for FEL amplification, the electron beam energy and its longitudinal distribution are also critical parameters. Even small energy modulations, at the level of a few percent with micrometer-scale spatial periodicity, can lead to the development of strong instabilities along the accelerator. These instabilities can cause significant amplification of such modulations and deterioration of the electron beam quality.

This process, known as microbunching instability, is particularly detrimental for externally seeded FELs, as the frequencies present in the electron beam can couple to the seed laser frequency, leading to a frequency mixing process that affects FEL amplification. As a result, seeded FELs based on imperfect electron beams lose their ability to generate Fourier-limited pulses, and their spectra become significantly deteriorated, often showing substantial side-band content (Fig 3).

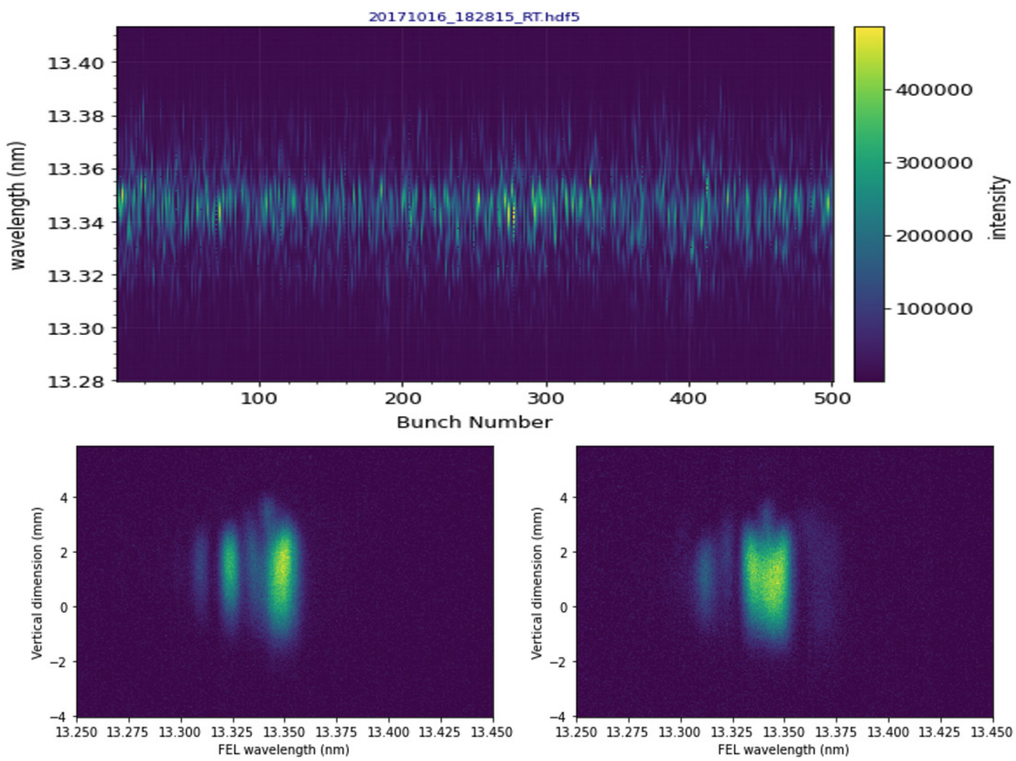

Fig 3. Impact of microbunching instability on FERMI FEL-1 performance. (a) Trend of FEL spectra and (b,c) two typical spectra for an electron beam strongly modulated by microbunching.

B. Preserving the seed coherence in FELs

A critical aspect of linear accelerator optimisation is the mitigation of the instabilities that can lead to microbunching in the final electron beam longitudinal phase space [40]. The use of a laser in the low-energy section of the accelerator to controllably increase the electron beam energy spread has been demonstrated as a viable method to suppress the microbunching instability [41-43]. This method, known as a ”laser heater,” is now widely used to optimize electron beam brightness in FEL accelerators and is a critical component for generating Fourier-limited pulses. The small increase in energy spread is well compensated by the improvement in electron beam quality, allowing not only for maximisation of the FEL intensity but also for improvement of the FEL spectral quality and coherence (Fig 4).

While the use of a laser heater is the most common approach for mitigating the deterioration of beam quality due to microbunching, recent studies have shown that microbunching gain can also be controlled with suitable settings of the linear accelerator components [44,45].

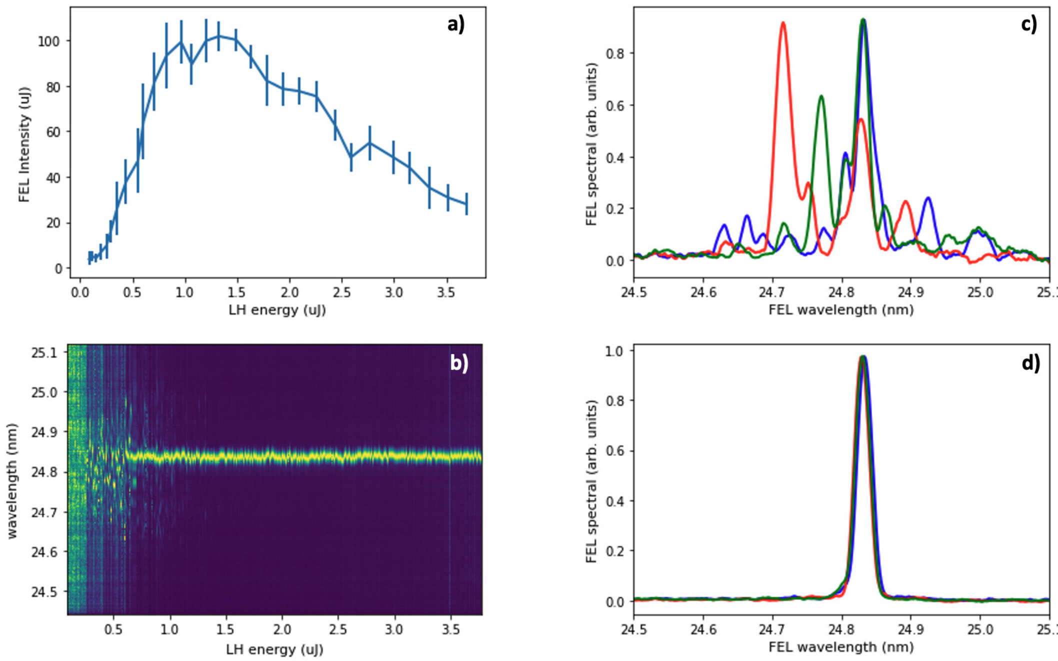

Fig 4. FEL sensitivity to laser heater settings. (a) FEL intensity versus Laser Heater (LH) pulse energy. (b) Normalized spectra as a function of LH pulse energy. Few randomly selected spectra for (c) low LH pulse energy (0.5 µJ) and (d) optimal LH pulse energy (1 µJ).

4 Conclusions

Externally seeded FELs have enabled the generation of powerful, fully coherent pulses down to the soft X-ray spectral region. This capability has unlocked important new scientific opportunities, particularly for experiments requiring high temporal coherence. The success of generating such pulses is strongly connected to the quality of the electron beam and the ability to suppress microbunching instability, which can lead to electron beam phase space distortions that destroy the laser-induced coherence. We have reported on methods used for controlling this instability, which have enabled FERMI to generate pulses suitable for coherent control experiments in the XUV spectral range.

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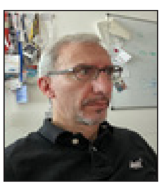

Enrico Allaria is a senior machine physicist at the FERMI Free Electron Laser facility at Elettra - Sincrotrone Trieste. He earned his Ph D from the Università di Firenze in 2007 and specialized in optics at the Istituto Nazionale di Ottica in 2022. Prior to relocating to Trieste in 2005, Enrico focused on controlling and synchronizing chaotic systems, including laser systems.

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