

Fully coherent soft x-rays from the nitrogen K-edge to beyond 1 keV

G. Penco^{1,*}, E. Allaria¹, L. Badano¹, A. Brynes^{1,†}, C. Callegari¹, G. Campri¹, F. Capotondi¹, A. Caretta¹, P. Cinquegrana¹, M. B. Danailov¹, G. De Ninno^{1,2}, A. Demidovich¹, M. Di Fraia^{1,8}, S. Di Mitri^{1,3}, E. Ferrari^{1,4}, L. Foglia¹, G. Gaio¹, L. Giannessi^{1,5}, G. Kurdi¹, S. Laterza¹, M. Malvestuto¹, M. Manfredda¹, C. Masciovecchio¹, I. Nikolov¹, E. Pedersoli¹, G. Perosa^{1,6}, O. Plekan¹, E. Principi¹, P. Rebernik¹, E. Roussel^{1,7}, N. Shafqat¹, A. Simoncig¹, P. Sigalotti¹, S. Spampinati¹, C. Spezzani¹, P. Susnjar¹, M. Travà¹, M. Veronese¹, and M. Zangrando^{1,8}

¹*Elettra-Sincrotrone Trieste S.C.p.A., S.S. 14-km 163.5 in AREA Science Park, 34149 Basovizza, Trieste, Italy*

²*Laboratory of Quantum Optics, University of Nova Gorica, Nova Gorica, Slovenia*

³*Department of Physics, University of Trieste, Via Alfonso Valerio 2, I-34127 Trieste, Italy*

⁴*Deutsches Elektronen-Synchrotron (DESY), DE-22603 Hamburg, Germany*

⁵*INFN Laboratori Nazionali di Frascati, Via E. Fermi 51, 00044 Frascati (Roma), Italy*

⁶*European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany*

⁷*Univ. Lille, CNRS, UMR 8523-PhLAM-Physique des Lasers Atomes et Molécules, F-59000 Lille, France*

⁸*CNR—Istituto Officina dei Materiali (IOM), Trieste, Italy*



(Received 23 June 2026; accepted 11 September 2026; published 7 October 2026)

Externally seeded free-electron lasers (FELs) provide radiation with full longitudinal and transverse coherence in the extreme ultraviolet and soft x-ray spectral ranges, inaccessible to conventional laser sources. Until now, externally seeded operation has been limited to the extreme ultraviolet and soft x-ray regime, while shorter wavelengths have been accessed primarily through stochastic self-amplified spontaneous emission processes (or derivatives thereof, one based on self-seeding) or through nonlinear harmonic generation at strongly reduced pulse energy. At the FERMI FEL facility, we have demonstrated stable operation in high-gain harmonic generation (HGHG) covering the nitrogen K-edge, most of the water-window spectral range, and approaching the oxygen K-edge by combining short-wavelength ultraviolet seeding (200 nm), increased electron beam energy, and preservation of an ultralow relative slice energy spread at the 10^{-5} level. The emitted radiation at such short wavelengths still exhibits the typical narrow bandwidth and wavelength stability of the HGHG scheme enabling, for example, time-resolved x-ray absorption spectroscopy measurements. Longitudinally coherent emission at 1 nm is obtained as the third harmonic of the fundamental FEL emission. Despite the lower intensity typical of nonlinear harmonic emission, these results demonstrate that external seeded FELs can be extended to nanometer wavelengths, establishing deterministic, fully coherent soft x-ray generation and surpassing the previous wavelength operation limits. This advance opens new opportunities for coherent control and nonlinear x-ray experiments that require both high photon energy and longitudinal coherence, and demonstrates a promising pathway toward further extension of externally seeded FELs to shorter wavelengths.

DOI: [10.1103/xlrl-kq7k](https://doi.org/10.1103/xlrl-kq7k)

I. INTRODUCTION

Temporally coherent radiation sources are a cornerstone of modern photonics, enabling access to light-matter interaction regimes characterized by high spectral purity, deterministic phase relationship, and precise control over the temporal and spatial structure of optical fields [1–4]. In particular, the availability of coherent radiation at short wavelengths has become

a central requirement for advancing our understanding of ultrafast and nanoscale phenomena in physics, chemistry, and materials science [5–7].

Within this landscape, free-electron lasers (FELs) occupy a unique position [8,9]. By exploiting the interaction between a relativistic electron beam and a periodic magnetic structure, an FEL can generate intense, ultrashort light pulses with exceptional brightness over a broad and continuously tunable spectral range, from the infrared to the extreme ultraviolet and hard x-ray [10–17]. This capability extends temporally coherent radiation into wavelength regions that are inaccessible to conventional laser sources based on population inversion transitions, opening new opportunities for probing matter with simultaneous atomic-scale spatial resolution and femtosecond to attosecond temporal resolution. Despite the transformative impact of FELs, achieving a high degree of temporal coherence remains a significant challenge. In particular, the control of longitudinal coherence at short wavelengths is a bottleneck

*Contact author: giuseppe.penco@elettra.eu

†Present address: Cockcroft Institute, Sci-Tech Daresbury, Keckwick Lane, Daresbury, Warrington WA4 4AD, United Kingdom.

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for many advanced spectroscopic and nonlinear applications. In a self-amplified spontaneous emission (SASE) FEL [9], a high degree of transverse coherence can be achieved as a result of the exponential gain and mode selection occurring during the amplification process. However, due to the intrinsically stochastic nature of the shot-noise-driven startup, the temporal coherence is limited: The amplification of intrinsic electron-beam shot noise leads to large pulse-to-pulse fluctuations and a noisy longitudinal structure of the radiation field, resulting in a relatively broad spectral bandwidth and limited temporal coherence. In order to overcome this limitation, several advanced schemes have been developed, including single-spike FEL [18–21], mode-coupled and high-brightness SASE [22], and self-seeding FEL [23,24]. Nevertheless, those schemes are nontrivial to implement and require sophisticated experimental setups. Furthermore, they are driven by radiation that has intrinsically poor temporal coherence at the second and higher orders.

In contrast, in a seeded regime, the FEL inherits the temporal and transverse coherence of a seed laser, delivering radiation fully coherent at all orders. This approach provides a deterministic route to coherence, overcoming the stochastic nature of SASE-based operation. In high-gain harmonic generation (HGHG) mode [25], an external laser imprints an energy modulation onto a high-brightness electron beam passing through a short undulator (the modulator). The electrons then traverse a dispersive section (i.e., a magnetic chicane) that converts this energy modulation into a density modulation (microbunching) with frequency components at the seed wavelength and its harmonics. The microbunched beam is then injected into a longer chain of undulators (the radiators) tuned to one of these harmonics, and coherent radiation is efficiently generated and amplified in the high-gain regime. The process transfers the coherence properties of the seed to the shorter wavelengths generated by the FEL, enabling the generation of pulses with unique properties in the extreme UV (EUV) and soft x-ray spectral range, including narrow spectral bandwidth, excellent pulse-to-pulse stability, and high-order coherence [26–28]. The longitudinal coherence has opened the path to coherent control experiments previously inaccessible in the EUV and soft x-ray regimes, such as the control of the relative phase of two-color FEL pulses with attosecond temporal resolution [5], the generation of phase-locked pulses [29], the observation of Rabi dynamics at short wavelengths [30], strong-field quantum control of ultrafast Rabi dynamics [31], and the generation of attosecond pulse trains [32].

While the harmonic conversion efficiency of single-stage HGHG limits its applicability to wavelengths down to ~ 15 nm, further extension of seeded FEL operation toward shorter wavelengths is achievable using more advanced schemes such as echo-enabled harmonic generation (EEHG) [33] or by implementing a two-stage configuration [34]. A two-stage HGHG process, in which the emission from the first stage, inheriting the coherence properties of the optical laser, seeds the second one, allows the spectral range to be further extended: After the experimental demonstration of this scheme at the Shanghai deep ultraviolet FEL (SDUV-FEL) [35], generation of fully coherent pulses in the soft x-ray regime was proved at FERMI [13], enabling subsequently

experiments at the carbon K-edge [36,37]. More recently, hybrid schemes such as cascaded EEHG-HGHG have also been explored to reach higher harmonic up-conversion factors and shorter wavelengths with fully coherent output [38–40].

A step toward shorter wavelengths has been performed by exploiting the nonlinear harmonic generation (NHG) regime [41–43]: Linearly polarized undulators naturally emit odd harmonics of the resonant wavelength on axis, so tuning FERMI in fundamental at 4–5 nm permits to reach the L-edge of transition metals (700–800 eV in third harmonic emission) [44]. It was demonstrated that the seed coherence is preserved in the nonlinear harmonics, which inherit the high temporal coherence of the fundamental FEL wavelength emission, already enabling a wide range of single-shot pump-probe spectroscopies in the soft x-ray domain. More recently, polarization control of NHG was demonstrated by properly adjusting the phase of the Apple II undulators [45], enabling circular dichroism experiments at the L-edge of magnetic transition metals [46]. However, experiments using NHG emission have to cope with the drawback of significantly reduced pulse energy, only a few percent of that available at the fundamental wavelength (i.e., tens of nanojoules per pulse), limiting their application to time-resolved dynamics in a linear regime. This want of intensity at the higher-order harmonics complicates the implementation of the method to study nonlinear processes, such as multiphoton multiple ionization, and of nonlinear spectroscopies such as four-wave mixing. Given the strong scientific interest in temporally coherent light sources at progressively shorter wavelengths [47], while retaining sufficient intensity to probe nonlinear processes, it is crucial to extend the capabilities of seeded FELs to enable the generation of fully coherent fundamental radiation in the soft x-ray range of the electromagnetic spectrum.

In this paper, we report the developments implemented at FERMI to achieve fundamental lasing across the nitrogen K-edge, and approaching the oxygen K-edge, extending the spectral range of time-resolved x-ray absorption spectroscopy (XAS) experiments. Access to the water-window energy region (~ 284 –543 eV) is of critical importance for soft x-ray FELs, as it substantially broadens their scientific reach. In this spectral range, the strong absorption contrast between carbon and oxygen enables element-specific imaging and spectroscopy of biological and organic materials in near-native environments, while maintaining nanometric spatial resolution and minimizing the need for exogenous labeling. In this context, the high degree of longitudinal coherence and spectral purity offered by the seeded scheme of FERMI enables pump-probe experiments with excellent shot-to-shot stability. In combination with an external laser, this approach ensures precise control of both wavelength and temporal jitter (less than 6 fs [48]), allowing for time-resolved studies with femtosecond resolution and high reproducibility. This has recently been demonstrated in experiments on gas-phase samples at the carbon K-edge [49], where the use of a seeded source provided a clear advantage over SASE operation. In particular, time-resolved x-ray photoelectron spectroscopy (TR-XPS) measurements were shown to be sensitive to nuclear dynamics, enabling their direct observation. This type of experiment requires FEL pulse intensities sufficiently high to

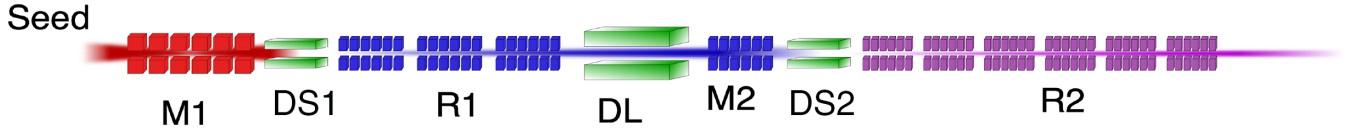


FIG. 1. FERMI FEL-2 line in double-stage HGHH configuration with fresh bunch, composed of the two modulators (M1 and M2), the two dispersive sections (DS1 and DS2) used to convert the energy modulation in density modulation, the electron beam delay line (DL), and the first- and second-stage radiators (R1 and R2).

ensure a satisfactory signal-to-noise ratio, a condition that is usually met only when operating on the first FEL harmonic, with pulse energies above $\sim 5\text{--}10\ \mu\text{J}$.

Furthermore, extending the fundamental FEL emission deep into the water-window region intrinsically improves the performance of nonlinear harmonic generation. Here, we demonstrate stable, fully coherent radiation at 1 nm, establishing the shortest wavelength ever reached by an externally seeded light source.

II. FERMI FREE-ELECTRON LASER

FERMI is a linac-driven free-electron laser comprising two lines: FEL-1, which can operate in single-stage HGHH or EEHG mode covering the 100–15 nm range, and FEL-2, based on a two-stage HGHH fresh-bunch scheme, which extends coverage down to 20–4 nm. In this scheme, the electron bunch is temporally delayed relative to the first-stage emission, allowing a fresh portion of the bunch to be seeded and enabling the generation of much shorter wavelengths [13]. A layout of the FERMI FEL-2 line is sketched in Fig. 1.

The FERMI electron beam routinely operates with a 500-pC bunch generated by a normal conducting high-brightness photoinjector, with a low transverse normalized emittance (usually between 0.5 and 1.0 mm mrad) and a peak current of about 60 A [50]. The beam is then accelerated by a normal conducting S-band linac and temporally compressed by a magnetic chicane (bunch compressor) to reach a peak current of about 600 A in a flat-top profile.

An FEL emits radiation at the fundamental wavelength given by [8]

$$\lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right), \quad (1)$$

where λ_u is the undulator period, $K = \frac{eB_u\lambda_u}{2\pi m_e c}$ the dimensionless undulator strength, B_u is the peak magnetic field, and $\gamma m_e c^2$ is the electron energy. From Eq. (1), to reach shorter wavelengths (at fixed λ_u and K), the electron beam energy must increase, and recently, a new accelerating section has been installed in the FERMI linac, increasing the maximum reachable energy from 1.5 to 1.67 GeV [51]. This translates to a potential $\sim 20\%$ reduction in the shortest attainable FEL wavelength reachable tuning the undulator with the same undulator strength (i.e., K).

An important figure of merit in the HGHH regime is the “bunching factor” that can be produced at the entrance of the radiator, which represents the normalized density modulation at harmonic h of the modulating wavelength [25]:

$$b_h = |J_h(-hAB)| \exp\left(-\frac{1}{2}h^2B^2\right). \quad (2)$$

Here, J_h is the h th-order Bessel function, A is the seed-induced energy modulation normalized to the electron time-slice energy spread σ_E , and $B = \frac{2\pi R_{56}\sigma_E}{\lambda_{\text{seed}}E}$, with R_{56} the dispersive section strength. To maximize the bunching at harmonic h , the seed energy modulation has to be about h times σ_E . In SASE regime, to allow the amplification of the shot noise in the high-gain FEL process, the relative slice energy spread (σ_E/E) has to be smaller than the FEL Pierce parameter ρ [8], which defines the fraction of electron beam power converted into radiation at saturation ($P_{\text{sat}} \sim \rho P_{\text{beam}}$). In an HGHH FEL, this requirement is more stringent, because the slice energy spread is increased by the seed energy modulation, so that in order to lase efficiently at harmonic h of the seed laser the following condition has to be met [52]:

$$\frac{\sigma_E}{E} \lesssim \frac{\rho}{2\sqrt{h^2 + 1}}, \quad (3)$$

where E is the beam energy. Equation (3) indicates that the relative energy spread must be kept as low as possible, particularly when targeting very short wavelengths (i.e., large h). Increasing the electron beam energy can partially relax this constraint, as ρ increases with beam energy, albeit weakly.

On the other hand, a significant margin of improvement exists on the overall slice energy spread of the electron beam that can be largely dominated by microbunching instability driven by longitudinal space charge force in the linac and coherent synchrotron radiation in the magnetic bunch compressors (see, e.g., Ref. [53] and references therein). For these reasons, a great effort has been spent in modeling, controlling, and suppressing the microbunching instability growth along the linac and in the spreader line. Readers are referred to Refs. [54–56] and references therein, for instability control in the dispersive region. A proper manipulation of both the momentum compaction and the chromatic dispersion invariant (H function) along the spreader enables the minimization of the instability driven by longitudinal space charge and coherent synchrotron radiation. The result is a high-brightness “cold” electron beam [57], with a measured σ_E of $48 \pm 3\ \text{keV}$, i.e., a relative slice energy spread of $\sigma_E/E \approx 2.9 \times 10^{-5}$ at 1.67 GeV. This value was obtained using a recently developed method described in Ref. [58]. It is based on an accurate modeling of the oscillating behavior of the FEL intensity when varying the dispersive section strength used to convert the seed energy modulation into density modulation, which finally allows to retrieve not only the slice energy spread of the electrons that effectively participate in the FEL process, but also the peak current and the seed spot size in the interplay region. The uncertainty on this estimation is related to the goodness of the fitting model, which in this case returns a confidence band of about 6%. This agrees with the estimation based on the optical-klystron method described in Ref. [59],

which, however, provides a measurement averaged over the whole electron bunch.

III. FERMI ACROSS THE NITROGEN K-EDGE IN FUNDAMENTAL EMISSION

Before the linac upgrade, it has been demonstrated that, in single-stage HGHG mode and seeding with a 240–260 nm laser, it is possible to lase up to $\lambda = 10$ nm (i.e., $h = 25$) but the pulse energy significantly drops for $h > 20$: A pulse energy of $\sim 6 \mu\text{J}$ was measured at 13 nm ($h = 20$) and $\sim 0.5 \mu\text{J}$ at 10 nm ($h = 25$) [57].

Going to shorter wavelengths therefore requires a two-stage HGHG scheme; however, it is crucial that the emission from the first stage is sufficiently intense to produce adequate bunching at the harmonic of the second stage [see condition (2)].

The standard FERMI seed pulses are based on nonlinear up-conversion of the infrared pulses from a Ti:sapphire regenerative amplifier into DUV by either third harmonic generation or pumping an optical parametric amplifier (OPA) followed by nonlinear mixing processes to reach the DUV wavelengths ranging 235–268 nm [60]. In order to reduce the harmonic frequency up-shift in the first stage and thereby achieve a stronger emission for more effective seeding of the second stage, one possible solution is to use the fourth harmonic of the Ti:sapphire laser, i.e., in the 200 nm range. For this purpose, a compact, collinear scheme for fourth harmonic generation was implemented, based on sum-frequency mixing of the fundamental and third harmonic pulses in a beta-barium borate crystal chain (see Ref. [61] for more details). The compactness of the scheme allowed the generation of the 200 nm seed pulse very close to its insertion point in the FEL line, therefore reducing the pulse stretching due to the material dispersion and losses due to the optical transport. Pulses with energy of up to 40 μJ , central wavelength of 197.8 nm, and pulse duration of 160 fs were generated and focused to a spot of 650 μm FWHM diameter in the center of the undulator.

By combining the linac energy upgrade (i.e., 1.67 GeV electron beam) with the almost complete suppression of the microbunching instability—resulting in an ultra-“cold” electron beam—and by seeding at 197.8 nm, we operated FERMI at the fundamental in two-stage HGHG with fresh-bunch injection, exploring the spectral range across the nitrogen K-edge (around $\lambda \approx 3$ nm, ~ 400 eV) and extending into the water window (~ 500 eV).

The first stage of FEL-2 was tuned to $h = 20$ (i.e., $\lambda = 9.89$ nm), delivering pulse energies of approximately 10 μJ , close to saturation, as indicated by simulations, with a good spectral quality ($\frac{\Delta\lambda_{\text{FWHM}}}{\lambda} \sim 5 \times 10^{-4}$), as shown in Fig. 2. This represents more than one order-of-magnitude increase in pulse energy with respect to the aforementioned FEL-1 operation at lower beam energy and ~ 260 nm seeding, as reported in Ref. [57]. Notably, this performance is achieved with a significantly shorter radiator, consisting of only three undulators compared to the six used in FEL-1.

Several combinations of harmonics of the first and second stages of FEL-2 were explored, and the performances in terms of pulse energy are reported in Fig. 3, compared

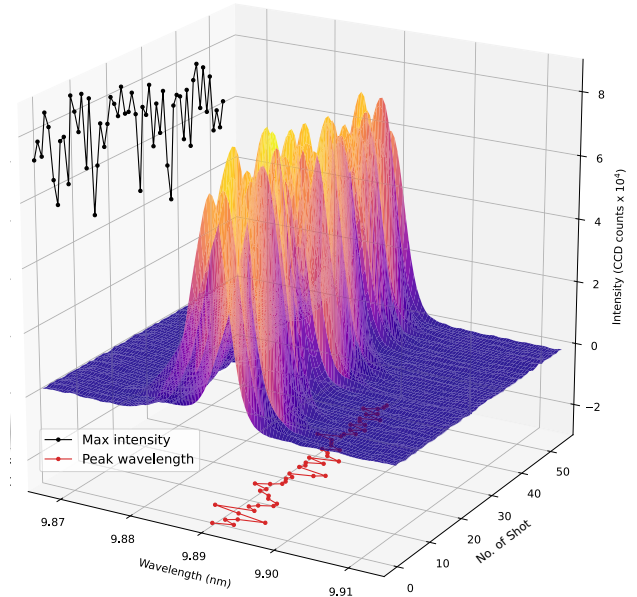


FIG. 2. FEL consecutive single-shot spectra at 9.89 nm emitted by the first stage of FERMI FEL-2 tuned at harmonic 20 (seed at 197.8 nm, e-beam energy at 1.67 GeV).

to what has been obtained by seeding at 263 nm using the same electron beam energy (1.67 GeV) and with a lower one (1.55 GeV). The error bars represent the combined effect of shot-to-shot machine parameter jitter (contributing 10%–15%) and long-time drifts (about 15%), the latter mitigated by optimizer software tools acting to minimize machine correlations [62,63]. There is a clear shift of the FEL radiation

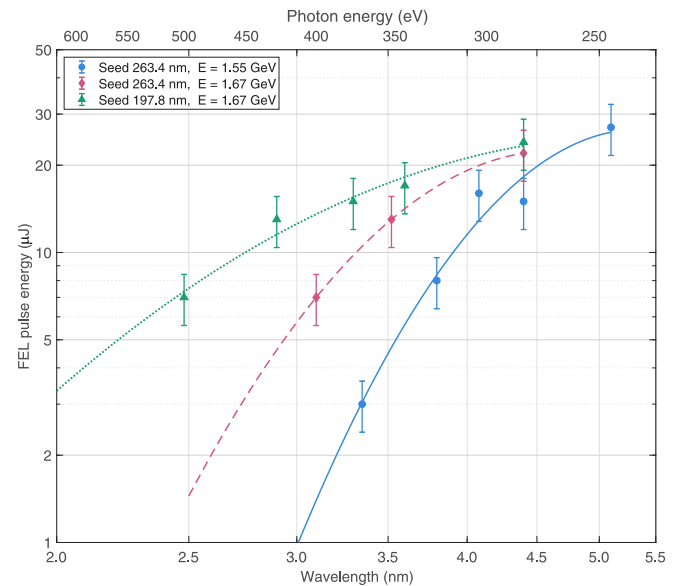


FIG. 3. Mean pulse energy measured with an electron beam energy of 1.67 GeV and a seed at 197 nm (yellow squares) and at 263.4 nm (red diamonds). Results are compared to the case with a lower energy beam (1.55 GeV) and a seed wavelength of 263 nm (blue cross). The error bars account for shot-to-shot machine jitter and long-time drifts (see text for details). Lines are drawn to guide the eye.

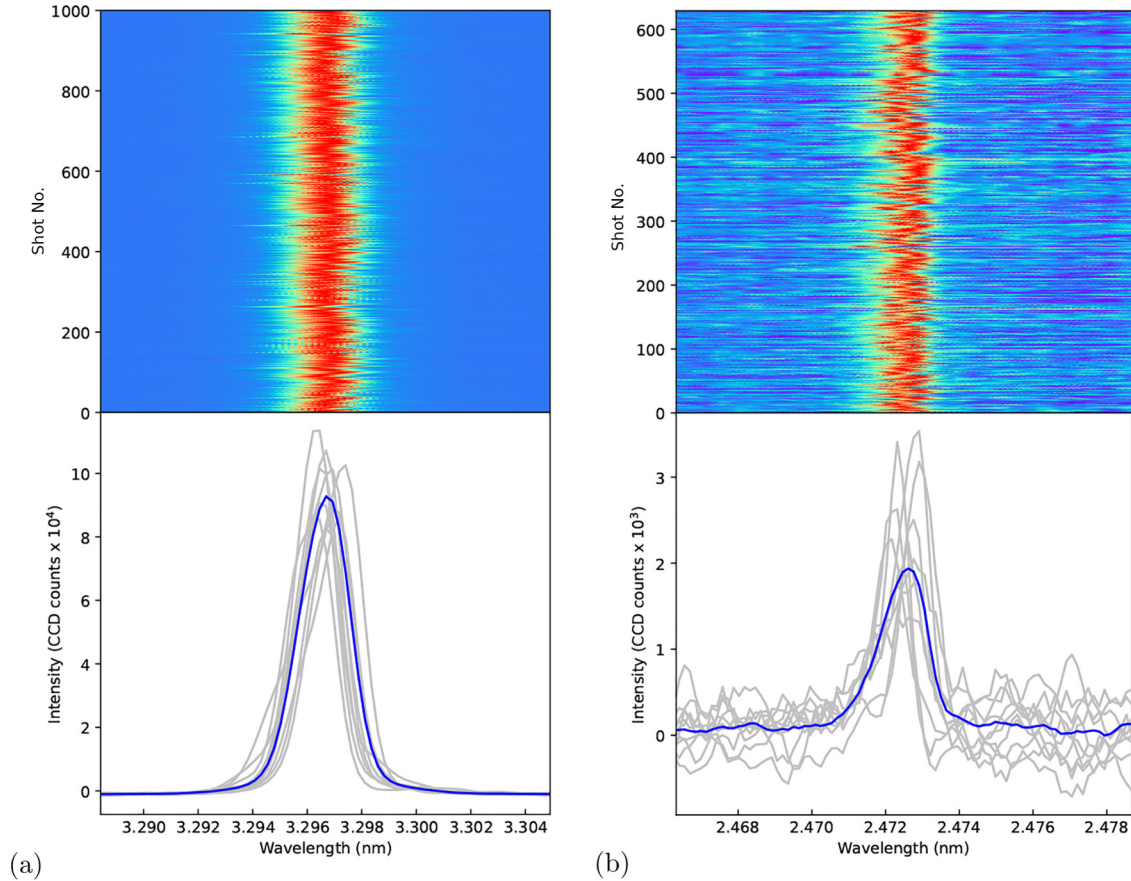


FIG. 4. Top: Intensity normalized shot-to-shot spectra at 3.30 nm [panel (a), 1000 shots] and at 2.47 nm [panel (b), 630 shots]. Bottom: Random single-shot spectra in grey and the average spectra in blue at 3.30 nm [panel (a)] and at 2.47 nm [panel (b)]. At 2.47 nm, the spectrometer was operated in the second diffraction order, where the diffraction efficiency is approximately ten times lower than in the first order, resulting in a reduced signal-to-noise ratio.

cutoff at FERMI from the carbon K-edge to the nitrogen K-edge at the fundamental emission, approaching the oxygen K-edge.

As representative cases, we report the performance obtained using the first stage at 9.89 nm and tuning the second stage to the third (3.30 nm, i.e., 376 eV) or the fourth harmonic (2.47 nm, i.e., 502 eV). The shots were acquired continuously at 50 Hz: A mean pulse energy of 18 μJ over 1000 shots with an rms shot-to-shot fluctuation of 16% and 6 μJ over 630 shots with an rms shot-to-shot fluctuation of 10% were measured, respectively. A high spectral quality was also obtained on this same set of shots, as shown in Fig. 4, where the corresponding shot-to-shot spectra at 3.30 nm and at 2.47 nm are plotted: A relative spectral bandwidth (FWHM) of $\sim 6.4 \times 10^{-4}$ and $\sim 6.8 \times 10^{-4}$ and a wavelength rms stability of $\Delta\lambda_{\text{rms}}/\lambda$ of 8.8×10^{-5} and 2.5×10^{-4} were measured, respectively. This confirms the high degree of temporal coherence of the FEL-2 output at the fundamental beyond the carbon K-edge.

The shown FEL spectra were recorded using the PRESTO spectrometer, installed along the FERMI photon transport and diagnostics system [64]. The photon beam was diffracted by a planar variable line-spacing grating, which focused the diffracted light onto a Ce:YAG (yttrium aluminum garnet) screen. The resulting fluorescence was imaged using a visible-light CCD (charge-coupled device), Hamamatsu C8800. The

spectral intensity was calibrated by simultaneously recording the spectrum and the FEL pulse energy using a calibrated photodiode positioned in the zero-order beam of the spectrometer. This cross-calibration enabled an accurate estimation of the shot-to-shot pulse energy also above the saturation threshold of the photodiode, which occurs at approximately 1 μJ . Due to the fixed-incidence geometry of PRESTO and a mechanical constraint that limits the minimum angular separation between the diffracted and zero-order beams to 6.8° , wavelengths below approximately 3.2 nm cannot be accessed in first diffraction order. Therefore, the spectra at 2.47 nm were recorded in second order, at the expense of a lower diffraction efficiency and consequently a reduced signal-to-noise ratio.

IV. FULLY COHERENT RADIATION AT 1 NM IN NONLINEAR HARMONIC GENERATION MODE

After characterization of the fundamental FEL emission at very short wavelengths, we subsequently investigated nonlinear emission at the third harmonic. Figure 5(a) shows consecutive single-shot spectra obtained at 1.099 nm and a selection of spectra: A wavelength stability $\delta\lambda/\lambda = 1 \times 10^{-4}$ and a relative FWHM spectral bandwidth of $\sim 9.0 \times 10^{-4}$ have been measured. Taking into account the efficiency of the photon transport, of grating diffraction, and of the

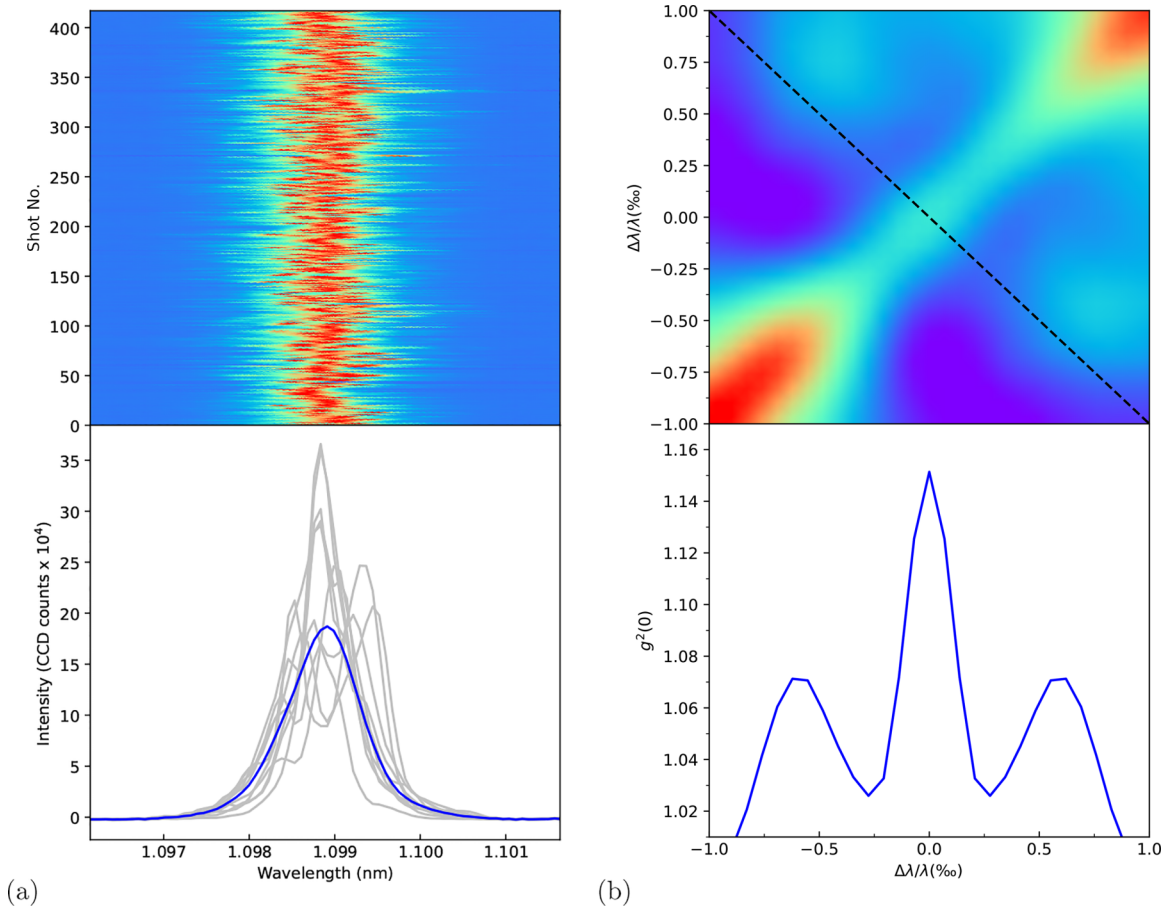


FIG. 5. (a) Intensity normalized shot-to-shot spectra (top) and a selection of randomly chosen single-shot spectra (bottom), obtained at FERMI at the third harmonic of the fundamental FEL emission: 1.099 nm (1128 eV). (b) Map of the $g^2(\lambda_1, \lambda_2)$ function with the dashed line indicating the antidiagonal (top), and the value of the g^2 function assumed along the antidiagonal (bottom).

detection, we can estimate a pulse energy at the source of about 15–20 nJ.

In order to verify the preservation of the high temporal coherence at this very short wavelength (i.e., at $h = 180$ of the seed laser), we have calculated the normalized second-order intensity correlation function, defined as [28]

$$g^2(\lambda_1, \lambda_2) = \frac{\langle I(\lambda_1)I(\lambda_2) \rangle}{\langle I(\lambda_1) \rangle \langle I(\lambda_2) \rangle}. \quad (4)$$

The results are plotted in Fig. 5(b) showing a laserlike level of intensity correlations at the wavelength of interest and well within the FEL bandwidth. In particular, the g^2 function assumes a maximum value of 1.15 on the antidiagonal, demonstrating a high degree of longitudinal coherence that approaches full coherence within experimental uncertainty. This small departure from ideal mathematical unity ($g^{(2)} = 1$) is typical for seeded FELs and is attributed to shot-to-shot fluctuations in electron beam parameters, residual intensity noise, and detector limitations, rather than a degradation of the intrinsic phase coherence. This value is very close to what is usually obtained at FERMI at longer wavelengths [28,44].

For data collected at the shortest wavelength, i.e., when operating in the nonlinear harmonic generation regime, the FEL beam transport was switched to an alternative branch optimized for the highest photon energy at FERMI. In

this configuration, the TARDI spectrometer [65] was used with an in-vacuum CCD (Andor iKon M934) instead of the Ce:YAG/visible-light CCD detection system employed in PRESTO. Along this branch, a direct cross-calibration of the spectral intensity is not possible. Nevertheless, by accounting for the reflectivity of the optical elements, the diffraction efficiency of the grating, and the detector quantum efficiency provided by the manufacturer, the pulse energy at the source could be estimated with an accuracy better than 10%.

V. CONCLUSION

We have demonstrated a substantial extension of the spectral reach of externally seeded free-electron lasers by combining short-wavelength ultraviolet seeding, increased electron-beam energy, and suppression of microbunching-driven energy spread growth. These developments enabled stable two-stage HGHG operation at the fundamental across the nitrogen K-edge, covering most of the water window and approaching the oxygen K-edge, while preserving the narrow bandwidth, wavelength stability, and shot-to-shot reproducibility that characterize seeded FELs.

At photon energies between 376 and 502 eV, corresponding to wavelengths down to 2.47 nm, the FEL delivered pulse energies in the multi-microjoule range, demonstrating that

fully coherent seeded operation can be extended well beyond the carbon K-edge while maintaining intensities suitable for time-resolved spectroscopy experiments.

Furthermore, by exploiting nonlinear harmonic generation, we demonstrated fully coherent radiation at 1.099 nm (1128 eV), establishing the shortest wavelength and highest photon energy reached so far by an externally seeded FEL. Measurements of the second-order intensity correlation function confirm the preservation of laserlike statistical properties and longitudinal coherence even at the 180th harmonic of the seed laser.

Looking forward, these advances provide a solid foundation for further extending seeded FEL operation deeper in the soft x-ray and for implementing sophisticated phase- and

amplitude-controlled experiments, enabling unprecedented exploration of ultrafast phenomena in matter. By bridging the gap between extreme ultraviolet and nanometer-scale coherent radiation, the results presented here mark a significant step toward next-generation x-ray light sources capable of fully exploiting the quantum and nonlinear dynamics of matter on ultrafast timescales.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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