High-repetition rate and coherent free-electron laser in the tender x rays based on the echo-enabled harmonic generation of an ultraviolet oscillator pulse

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Fine time-resolved analysis of matter—i.e., spectroscopy and photon scattering—in the linear response regime requires a fs-scale pulsed, high repetition rate, fully coherent x-ray source. A seeded free-electron laser (FEL) driven by a super-conducting linac, generating $10^8$–$10^{10}$ coherent photons at 2–5 keV with about 0.5 MHz of repetition rate, can address this need. The seeding scheme proposed is the echo-enabled harmonic generation, alimented by a FEL oscillator working at 13.6 nm with a cavity based on Mo-Si mirrors. The whole chain of the x-ray generation is here described by means of start-to-end simulations. Comparisons with the self-amplified spontaneous emission and a fresh-bunch harmonic cascade performed with similar electron beams show the validity of this scheme.

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I. INTRODUCTION

Fine time-resolved analysis of matter is currently performed with synchrotron radiation (SR) sources or with x-ray free electron lasers (FELs), whose extremely brilliant pulses are able to detect matter in highly excited states dominated by non-linear response. Spectroscopic studies and photoemission experiments require probes with fluxes smaller than $10^8$ photons/pulse and MHZ-class repetition rates, for remaining below the linear response threshold and collecting adequate statistics. Current FELs’ photon number exceeds this level by 2–4 orders of magnitude, requiring severe attenuation with huge waste of energy. On one hand, sources based on warm linacs, operating at 10/120 Hz, are inadequate for collecting statistics for high resolution spectroscopy. On the other hand, signals like the one by EuXFEL [1,2], shaped in thousands micropulses grouped in 10 macropulses per second, are also nonideal for spectroscopy as both attenuation is needed and the high repetition rate of the micropulses overrun detector and pump-probe set-up capability. SASE fluctuations severely limit the use of FELs in x-ray spectroscopy and full seeding, routinely implemented at FERMI@Elettra [3] and SXFEL [4], should be extended to tender/hard x-ray energies.

There is therefore scientific need and ample room for a novel type of source: a source delivering to the sample $10^7$–$10^8$ photons in 10 fs coherent pulses at 0.5–2 MHz in the tender/hard x-ray range, thus bridging the gap in time resolution and average photon flux between the most advanced SR and the current FELs. These requests are addressed by conceiving a tailored seeded FEL driven by Linacs based on Super-Conducting cavities, providing $10^8$–$10^{10}$ coherent photons at 2–5 keV, at about 1 MHz of repetition rate. In the seeded FEL configuration, an external coherent pulse imprints its temporal phase on the electron beam at the undulator entrance. The direct seeding [5] is not possible in the soft-hard x-ray range due to the lack of high-power coherent seeds at these wavelengths, while self-seeding processes [6,7] only achieve partial coherence. High gain harmonic generation (HGHG) multi-stage cascades [8], seeded by the harmonics of an IR laser generated in crystals [9] or in gases [10–13], have been demonstrated and applied up to few nm wavelengths [3]. However, their implementation in the tender/hard x-ray range is highly demanding, while the extension to higher repetition rates, obtained by using oscillators [14] or lasers in cavity [15], has been studied sofar only theoretically. As demonstrated at SXFEL [4], a step toward high repetition rate seeded FELs is also foreseen by using an optical klystronlike configuration, allowing us to reduce the requirement for the peak power of the seed laser. FEL oscillators [16–21] or regenerative amplifiers [22–26]...
could directly produce coherent x rays [14,27], but the operational scenario proposed so far, with electrons at several GeVs, impedes their realization in small/medium size research laboratories. UV/soft x-ray coherent radiation has been generated with the echo-enabled harmonic generation (EEHG) [28–32], a technique which requires two coherent radiation pulses, usually delivered by optical lasers, seeding the electron beam in two sequential modulators interspersed by a strong dispersive section. A second dispersive section and the radiator are placed downstream. As explained in Refs. [28,29], the combination of energy modulation and dispersion, replicated twice, warps the electron longitudinal phase space, producing a significant bunching on very high harmonics which drives the emission of a short wavelength coherent pulse in the radiator. A combined EEHG-oscillator scheme with two oscillators as modulators has also been proposed [33].

In this paper, we show the operation of a FEL in the tender X-ray range, based on EEHG. We propose a FEL Oscillator in the far ultraviolet frequency range as seeding source. The advantage of such a scheme is twofold: the oscillator operation, combined with an electron beam accelerated in a superconducting linac, increases the device repetition rate by many orders of magnitude (4–6). Moreover, since the oscillator frequency and peak power are much higher than the ones of a conventional laser, the soft-hard x-ray range can be more easily reached by a lower harmonic number.

II. LAYOUT OF THE COHERENT SOURCE AND SIMULATIONS

The electron beam is supposed to be generated by an accelerator similar to the project MariX’s (multidisciplinary advanced research infrastructure for the generation and application of x rays) [34,35], whose compact footprint with a total length of about 500 m and contained cost should permit its construction also in medium-size research infrastructures or within university campuses. MariX is based on the innovative design of a two-pass two-way superconducting linear electron accelerator [35], equipped with an arc compressor [36,37] to be operated in CW mode at 1 MHz. The characteristics of the electron beam are listed in Table I. As studied and demonstrated in Ref. [38], the superconducting technology allows to achieve low jitters and fluctuations of the electron beam. These increased stability conditions, together with the seeded mode FEL operation, give the possibility to produce a fully coherent, high repetition rate and highly stable x-ray source.

Figure 1 shows the scheme of the source. After the acceleration stage, successive electron bunches are alternatively driven in the oscillator or matched to the EEHG undulator device. The electron beam alimenting the oscillator is extracted upstream the linac end at an energy of 2 GeV, while the ones entering the EEHG device may have the same energy or be further accelerated. The oscillator is constituted by a 9 m long undulator segment with period \( \lambda_0 = 5 \text{ cm} \) and produces 70 \( \mu \text{J} \) of intracavity radiation at \( \lambda_0 = 13.6 \text{ nm} \). It is embedded into a folded ring cavity composed by 4 mirrors, two of which focusing, with optics heat loading requiring an intelligent cooling system. For an oscillator repetition rate of 0.5 MHz, the round trip length \( L_e \) is 600 m and the distance between two mirrors is \( L_e / 4 = 150 \text{ m} \). The oscillator supermodes [16] are calculated fully numerically [14,23] by extracting the radiation field simulated by GENESIS1.3 [39] from the oscillator, driving it through the optical line accounting for mirrors and propagation, and superimposing it on the successive electron bunch. The microscopic distribution of the electron beam is changed shot to shot in order to simulate the passage of a sequence of different bunches. After the passage into the oscillator, the electron bunch is deteriorated by the radiation process and driven to the dump.

Figure 2 presents the intracavity pulse temporal and spectral densities of the seed at saturation, whose Table II summarizes the characteristics of the intracavity seed pulse at saturation. After an optical transport line that splits it in two pulses, the seed is synchronized to the electron bunches at the beginning of both modulators. Energy losses along the transport line have been taken into account. The oscillator seed pointing stability and transverse overlap with the electron bunches after the transport line will be checked and adjusted with multipurpose stations and beam stabilization systems as the ones described in [40,41].

To obtain radiation in the range \( \lambda = 5–2 \text{ Å} \), namely 2–5 keV, with the MariX’s moderate energy electron bunch (2.5–3.8 GeV), a short period radiator must be considered. From the resonance relation \( \lambda = \frac{2 \pi}{a_w} (1 + a_w^2) \) \( (a_w \text{ is the undulator parameter and} \quad \gamma \text{ the electron Lorentz factor}) \), taking a maximum magnetic field \( B = 1 \text{ T} \) corresponding to \( a_w = 0.98 \), we can deduce that an undulator period of \( \lambda_w = 1.5 \text{ cm} \) is suitable. Besides, starting from a seed at \( \lambda_o = 13.6 \text{ nm} \), a significant electron bunching on harmonics’ order \( n \) in the range from 25 to 70 is required. By following the unidimensional model based on plane waves exposed in Ref.s [28,29], the electron bunching is expressed in terms of four free parameters, namely the dispersion strengths of the two chicanes \( R_{56,1} \) and \( R_{56,2} \) and the normalized electric fields of the seeds:

\[
\begin{array}{|l|l|}
\hline
\text{Electron beam energy} & \text{GeV} & 2–3.8 \\
\text{Charge} & \text{pC} & 30–50 \\
\text{Current} & \text{kA} & 1.6 \\
\text{rms normalized emittance} & \text{mm mrad} & 0.3–0.5 \\
\text{rms relative energy spread} & 10^{-4} & 3 \\
\text{Electron beam duration} & \text{fs} & 12 \\
\text{Slice energy spread} & 10^{-4} & 4.2 \\
\text{Slice normalized emittance} & \text{mm mrad} & 0.3 \\
\hline
\end{array}
\]
end is obtained for \( n = 25 \), corresponding to \( \lambda = 5.44 \text{ Å} \)
with \( R_{561} = 132 \mu \text{m} \) and \( R_{562} = 4.72 \mu \text{m} \). The power
growth in this case is shown in Fig. 3, its central windows
showing the electron phase spaces after the first modulator
(a), after the first chicane (b), after the second modulator (c)
and at the radiator entrance (d). The initial bunching on
\( \lambda = 5.44 \text{ Å} \) (in violet) reaches a peak of 4.5% on the bunch,
while the rms energy spread increases from 0.03% to
0.045% in the modulators and in the chicanes. These
parameters are sufficient to trigger a consistent FEL
emission in the radiator, and the radiation is extracted at
the minimum bandwidth position, occurring after 12 m of
radiator (about 16 m of the total device). The neat single
spike structures in power and spectral amplitude at the end
of the undulator, are shown in the inner windows in blue
and red respectively, compared with the corresponding
SASE profiles extracted after 40 m of undulator. Source
coherence and stability are evaluated through the modulus
of the complex coherence degree:

\[
\Gamma_{ij}(\tau) = \left| \frac{\int dt E_i(t) E_j(t-\tau)}{\sqrt{\int dt |E_i|^2 \sqrt{\int dt |E_j|^2}}} \right|
\]

between two different generic pulses \( i \) and \( j \) generated by
different electron beams (\( \Gamma_{ij} \)) or for one single pulse
(\( \Gamma = \Gamma_{ii} \)), where \( E_i \) and \( E_j \) are the electric fields of
the pulses as function of time. These two quantities are shown
vs \( \varsigma = c \tau \) for \( n = 25 \) in the right windows of Fig. 3,
together with those of the SASE case at saturation. The
FWHM coherence length of the EEHG pulse is \( \Omega_s = 0.67 \mu \text{m} \),
about 4 times the corresponding SASE’s. The equal time coherence between different pulses \( \Gamma_{ij}(0) \) is
close to 1, differently from the SASE’s of \( 10^{-4} \). The
FWHM mutual coherence length, quantifying the shotto-shot stability, is 0.1 \( \mu \text{m} \), compared to 0.015 \( \mu \text{m} \) of the
SASE one. The EEHG coherent source provides an

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**FIG. 1.** Scheme of the echo-enhanced harmonic generation FEL. \( b_1 \) and \( b_2 \): electron bunches alternatively sent in the oscillator and in
the undulators. FEL Oscillator undulator: \( \lambda_w = 5 \text{ cm} \), \( a_w = 3.71 \), total length 9 m. \( m_1, m_2, m_3, m_4 \): oscillator cavity mirrors. D: beam
dump. \( m_5, m_6, m_7, m_8 \): mirrors of the optical line that splits and couples the seed to the modulators. \( m_5 \) and \( m_6 \): beam splitters. First (\( M_1 \))
and second (\( M_2 \)) modulators: \( \lambda_w = 5 \text{ cm} \), \( a_w = 3.71 \), respectively 1.6 m and 1.5 m long. The two chicanes \( C_{1,2} \) are both 0.45 m long.
Radiator: about 20 m long, \( \lambda_w = 1.5 \text{ cm} \), maximum magnetic field: about 1 T.

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**FIG. 2.** Signal (a) and spectrum (b) of the intracavity power of the oscillator at saturation.

**TABLE II.** Characteristics of the seed, generated by the FEL oscillator with undulator length \( L_w = 9 \text{ m} \). The repetition rate of
the source is 0.5 MHz. \( S = \text{Photons/s/mm}^2/\text{mrad}^2/\text{bw}(\%) \).

| Parameter                      | Value                          |
|--------------------------------|--------------------------------|
| \( \lambda_O (\text{nm}) \)    | 13.6                           |
| Photons/shot                   | \( 4.5 \times 10^{12} \)       |
| E\( (\mu \text{J}) \)          | 2.27 \times 10^{18}           |
| Bandwidth relative             | \( 1.7 \times 10^{-3} \)       |
| Div(\text{mrad})               | 50                             |
| Size(\mu \text{m})            | 80                             |
| Peak brilliance($)             | \( 2.4 \times 10^{31} \)       |
| Average brilliance($)          | \( 8 \times 10^{22} \)        |
ultrashort pulse with 5 μJ of energy per shot at \( \lambda = 5.44 \) Å, corresponding to \( 1.4 \times 10^{10} \) photon/shot at 0.5 MHz or \( 0.7 \times 10^{16} \) photons/s, while the SASE source reaches \( 14.7 \times 10^{16} \) photons/s at 1 MHz. Even if characterized by a smaller number of photons, bandwidth, coherence and collimation of the EEHG give an average brilliance of \( 1.7 \times 10^{24} \) photons/s/mm²/mrad²/bw(‰), being only a factor 5 smaller than the corresponding SASE’s. Working points covering the range between 5.44 and 2.7 Å, namely \( n = 25, 35, 45, \) and \( 50 \), are presented in Table III and compared to similar SASE cases after 40 m of undulator. Electron beams with progressively larger energies allow to reach shorter wavelengths. Figure 4 presents powers and spectral amplitudes for both SASE (black) and EEHG (red) cases for \( n = 35, 45, 50 \). The case with \( n = 35 \) is performed with an electron beam of about 3 GeV and delivers \( 1.7 \times 10^9 \) photons/shot at 3.88 Å, extracted after 16 m of radiator with an average brilliance of

![Figure 3](image-url)  
FIG. 3. Radiation energy \( E(J) \) vs z(m). In blue, radiation at \( \lambda_o = 13.6 \text{ nm} \) in the modulators. In violet, radiation at \( \lambda = 13.6/25 \text{ nm} = 5.44 \) Å in the radiator. Point (a) is the 1st modulator end, (b) 1st chicane end, (c) 2nd modulator end and (d) 2nd chicane end. Inner figures: (i) bunching on the 25th harmonics at the end of the 2nd chicane, (ii) power density, (iii) spectral amplitude (SASE at 40 m and EEHG at the radiator exit). Windows (a), (b), (c), (d): electron phase space, electron Lorentz factor \( \gamma \) vs seed phase \( \phi \), in the corresponding points. (e) and (f): SASE (red) and EEHG (blue) coherence degree for one pulse \( \Gamma \) and for different pulses \( \Gamma_{ij} \) vs \( \varsigma = c \tau \). Dotted segments: FWHM coherence lengths.

**Table III.** SASE (extracted at saturation), EEHG (extracted at minimum bandwidth) and fresh-bunch HGHG cascaded FEL characteristics, \$ = Photons/s/mm²/mrad²/bw(‰).

| Mode                  | SASE | EEHG | HGHG | SASE | EEHG | HGHG | SASE | EEHG | HGHG | SASE | EEHG |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| Harmonic number       |      |      |      |      |      |      |      |      |      |      |      |      |
| Wavelength Å          | 5.44 | 5.44 | 5.44 | 3.88 | 3.88 | 3.88 | 3.02 | 3.02 | 3.02 | 0.9  | 0.9  | 0.9  |
| \( \gamma \)          | 5216 | 5216 | 5216 | 6151 | 6151 | 6151 | 6991 | 6991 | 6991 | 7352 | 7352 | 7352 |
| Undulator length m    | 40   | 16   | 32   | 40   | 20   | 20   | 22   | 22   | 22   | 40   | 40   | 40   |
| Energy \( \mu J \)    | 58   | 5.1  | 7    | 58   | 0.9  | 3.2  | 46   | 0.9  | 0.9  | 42   | 0.18 |
| Photon/shot \( 10^9 \)| 158  | 13.9 | 19   | 112  | 1.74 | 6.2  | 69   | 1.36 | 57   | 0.245|
| Bandwidth %           | 0.1  | 1    | 0.37 | 0.17 | 0.9  | 0.4  | 0.32 | 0.6  | 0.3  | 0.5  | 0.35 |
| Length fs             | 10   | 1.5  | 3    | 10   | 0.8  | 4.5  | 10   | 1    | 1    | 1    | 1    |
| Divergence μrad       | 3.7  | 3.9  | 3.6  | 2.7  | 3.2  | 5.1  | 2.2  | 2.5  | 2.05 | 2.3  |      |
| Pulse size μm         | 35   | 27   | 24   | 32   | 25   | 29   | 27   | 25   | 27   | 30   |      |
| Photon/s \( 10^{15} \)| 158  | 7    | 4.7  | 112  | 0.87 | 3.1  | 69   | 0.67 | 57   | 0.09 |
| Average brilliance     | \( 10^{23} \)$ | 94   | 17   | 37   | 151  | 3.39 | 5.51 | 325  | 5.71 | 57   | 0.51 |
| Coherence length μm   | 0.17 | 0.67 | 1.3  | 0.11 | 0.52 | 1    | 0.1  | 0.5  | 0.1  | 0.3  |      |
3.8 GeV, the system produces electron energy to the maximum value foreseen for energy of 3.6 GeV,
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radiation profile for is from 5 (1023
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FIG. 4. SASE (black) and EEHG (red) power and spectral radiation profile for n = 35, 45, 50. (R56,1 = 184.7 μm, R56,2 = 4.86 μm), 45 (R56,1 = 281.6 μm, R56,2 = 6.58 μm), and 50 (R56,1 = 293.2 μm, R56,2 = 6.07 μm). SASE power vs s = ct is on the left axis, EEHG power on the right. Spectra are in arbitrary units and not in scale.

3.4 × 1023 photons/s/mm²/mrad²/bw(%) with an energy of 3.6 GeV, 1.36 × 10⁹ photons/shot at 3.02 Å (n = 45) can be generated with an average brilliance of 5.7 × 1023 photons/s/mm²/mrad²/bw(%). Pushing the electron energy to the maximum value foreseen for MariX, 3.8 GeV, the system produces 2.4 × 10⁸ photons/shot at 2.7 Å (n = 50) with a brilliance of 5.7 × 1023 photons/s/mm²/mrad²/bw(%). The coherence length is from 5 (n = 35) to 3 (n = 50) times the corresponding SASE’s, while the stability is larger by a factor from 10 (n = 35) to 20 (n = 50). Since these estimations widely exceed the target values set by the scientific case, the EEHG source will be capable to satisfy the conditions requested by the envisaged experiments, considering a safety margin compensating all the degradations due to errors, misalignment, jitters and the losses dealing with the transport of the photon beams to the experimental hutch. The comparison between the results of the EEHG technique and those of a fresh-bunch HGHG cascade, performed with a similar electron beam and with the same oscillator as seeding source [14], shows a substantial equivalence in terms of number of emitted photons for n = 5 × 5 and a better performance of the HGHG cascade for n = 7 × 5, when the induced energy spread limits the EEHG radiation. However, the HGHG efficiency decreases very rapidly at higher harmonics (n > 35) and radiation levels comparable with the EEHG’s cannot be achieved. A total of four different electron bunches per shot are needed for the fresh-bunch technique, while for the EEHG only one bunch for the oscillator and one for the FEL are required, doubling, in proportion, the radiation repetition rate. Regarding coherence, a better performance of the HGHG cascade is observed, due to the more direct transfer of the coherence properties from the seed to the radiation. The advantage of the EEHG is a larger tunability and versatility of the source, that permits to generate intense (10¹⁰ – 10⁹ photons/shot), ultrashort (down to 1 fs) pulses at all the harmonics n of the seed up to n = 50 and not only at those corresponding to the product of two odd integer numbers (n = 5 × 5, 3 × 9, 7 × 5…).

III. CONCLUSIONS

A new generation accelerator complex is at the core of this coherent and compact facility dedicated and optimized to ultra-fast coherent x-ray spectroscopy and inelastic photon scattering, and to highly penetrating x-ray imaging of mesoscopic and macroscopic samples. The x-ray generation scheme here studied relies on a conventional EEHG device seeded by a far-UV FEL Oscillator and reaching high harmonic orders up to n = 50. Its comparison with a SASE FEL performed with a similar electron beam proves the much higher stability and coherence of the produced pulses. The major advantage with respect to a fresh-bunch three-stage FEL cascade seeded by the same oscillator is given by the tunability and simpler setup of the EEHG scheme. Such facility will be intrinsically multiuser and multidisciplinary as of the research performed and science output.
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