High repetition rate and coherent Free-Electron Laser in the X-rays range tailored for linear spectroscopy

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Introduction

We present a comparison between three different methods for producing truly coherent X-ray pulses, conceived for the MariX (Multidisciplinary Advanced Research Infrastucture for the generation and application of X-rays) project [1,2], a compact infrastructure based on a two-pass two-way SC linac equipped with an arc compressor, to be operated in CW mode at 1 MHz. The FEL source is tailored for time-resolved spectroscopic applications with coherent X-rays, which require $10^7 - 10^{10}$ photons per 10 fs-long pulses at several hundreds kHz of repetition rate. The start-to-end simulations rely on an electron beam with a Gaussian longitudinal current profile, having the same properties of the electron beam accelerated through the MariX complex (and listed in the table):

electron beam energy	GeV	1.6-3.8	rms normalized emittance	mm mrad	0.3-0.5
Charge	pC	8-50	rms relative energy spread	10^{-4}	2-4
Current	kA	1.3-1.6	electron beam duration	fs	2.5-16

The FEL simulations have been performed with GENESIS 1.3 [3].

Motivation

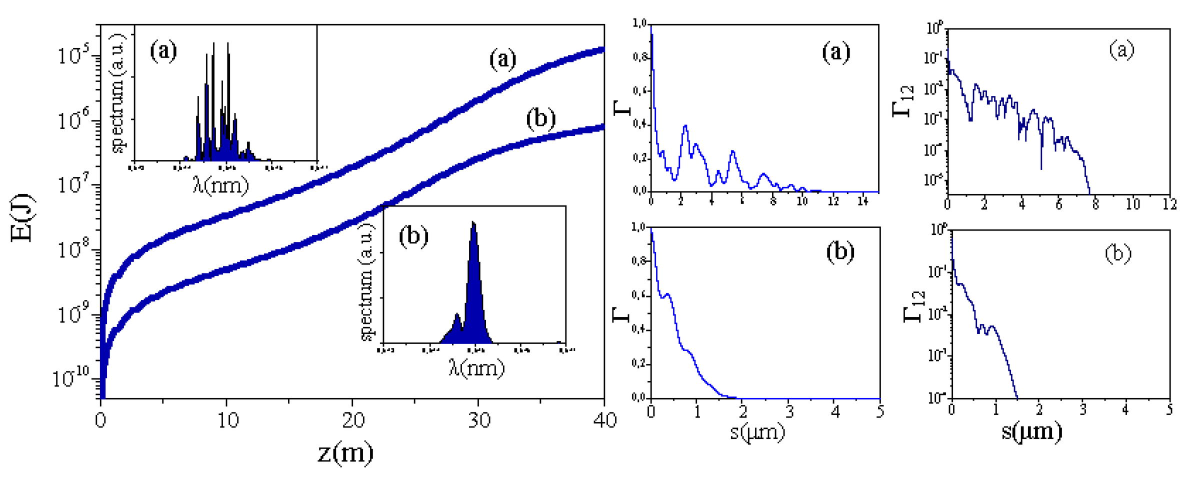
If full coherence is needed, a seeded amplifier needs to be implemented, where the emission is forced by an external coherent source. A seeding source for short wavelength FELs should have a sufficiently high power level, able to overcome the shot noise level [4]:

$$P_{sn} = \omega_0 \rho^2 \Upsilon mc^2 \quad \text{with} \quad \begin{cases} \omega_0 \text{ emission frequency} \\ \rho \text{ FEL Pierce parameter} \\ \Upsilon \text{ normalized electron energy} \end{cases} \longrightarrow \frac{P_{seed}}{P_{sn}} \approx 10^3 - 10^4$$

For this reason, the direct seeding is not possible in the soft-hard X-rays range. We investigate three seeding schemes with quite short installations, focusing on their implementation in the linear spectroscopy range (5 – 2.5 keV)

SASE mode

SASE emission at 5.44 Å



Coherence degree

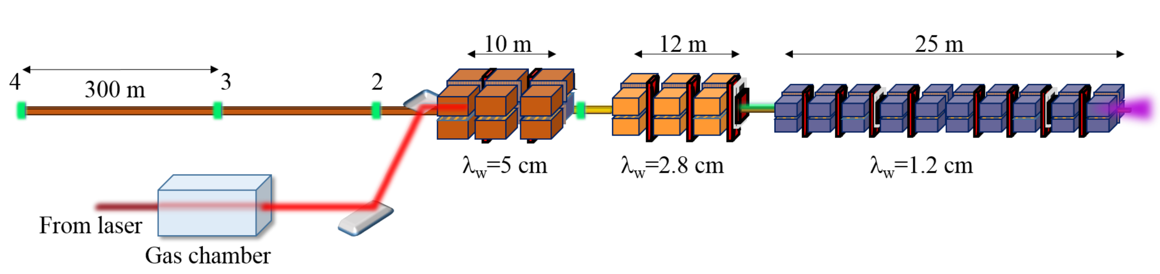
$$\Gamma_{12}(\tau) = \left| \frac{\int dt E_1(t) E_2(t-\tau)}{\sqrt{\int dt |E_1|^2} \sqrt{\int dt |E_2|^2}} \right|$$

Case (a) refers to the high charge (50pC) multi-spike SASE regime, case (b) to low charge (8pC) single spike regime. Left panel: radiation growth vs undulator coordinate. Right panels: one shot coherence degree and mutual coherence degree between two uncorrelated shots vs s = c for high (a) and low (b) charge.

Harmonic cascade seeded by High Harmonic Generation in gas

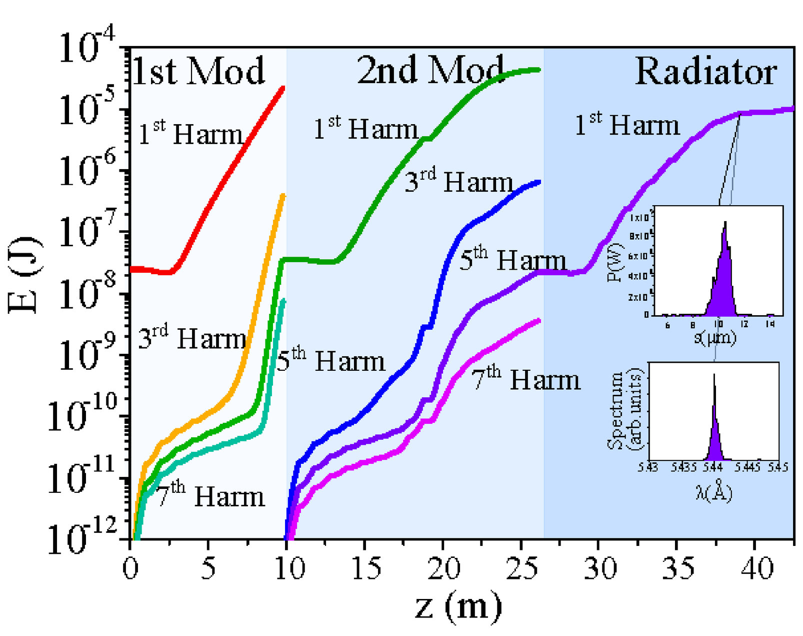
The seeding setup is based on the HHG technique, which allows to produce coherent high-order harmonics of an ultra-short laser pulse through its interaction with a noble gas [5].

λ_{seed} = 13.6 nm (H 59°)
E_{seed} = 10-15nJ



The cascade consists of two stages of longer period (5 cm and 2.8 cm) modulators and a short period (1.2 cm) undulator as radiator. The fresh bunch injection technique has been considered, by superimposing the seed on a part of the electron beam not deteriorated by the radiation process in the previous stage.

The results starting from 13.6 nm and up-shifting the frequency by a factor 5x5 are presented:



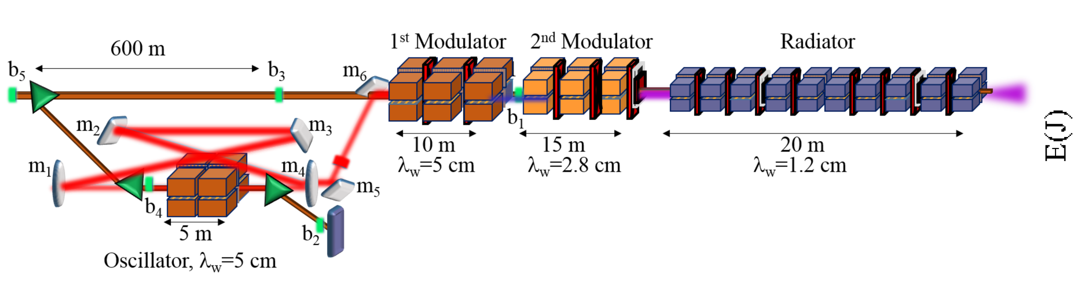
Characteristics of the radiation yield from the HHG-seeded cascade.
The repetition rate of the source is limited to a maximum of 100 kHz.

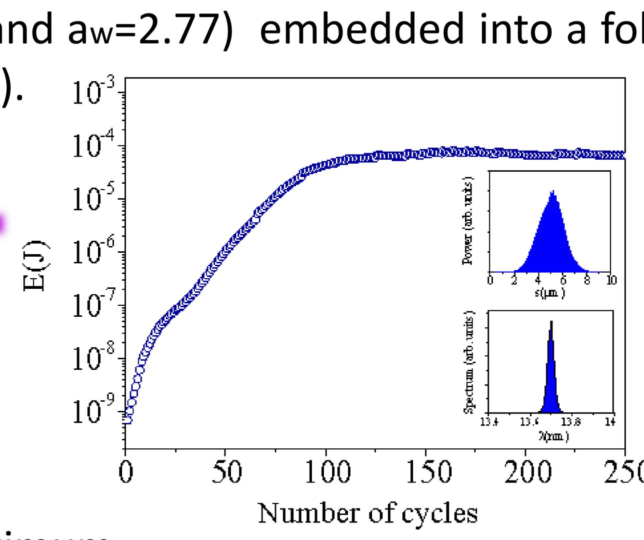
λ	0.544 nm	E	10 μJ
N/shot	10^{10}	N/s	10^{15}
bw	0.07%	length	2-3 μm
div	35 μrad	size	75 μm

5x5 cascade seeded by HHG: FEL radiation energy vs undulator position, temporal power distribution and spectrum (in the boxes) extracted at about 40 m.

Harmonic cascade seeded by an FEL oscillator

The seed is delivered by an EUV FEL oscillator (FELO), alimented by the electron beam at 2.04 GeV and constituted by an undulator segment (5 cm period and a_W=2.77) embedded into a folded etalon with a minimum of 4 mirrors (at least two of them focusing).



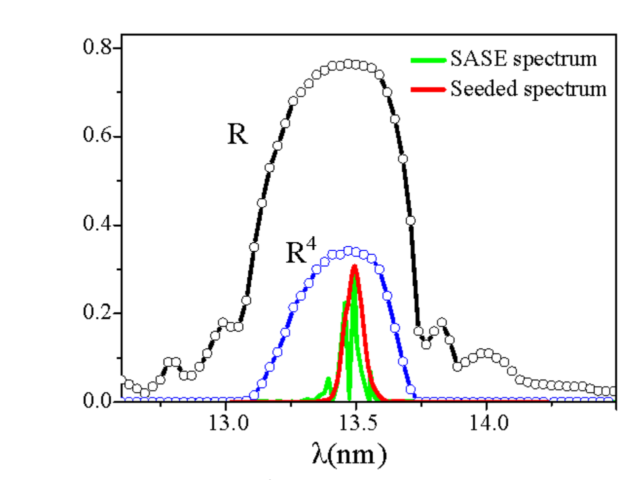


Intracavity energy vs the number of cycles.
In the boxes: radiation amplitude and spectrum at saturation.

The oscillator works at 13.6 nm, the optimum wavelength for Mo/Si multilayer mirrors [6,7].
Both the spectral and angular filtering of the mirrors is ineffective, because the mirror acceptance (about 0.15 rad [8]) is much larger than the divergence of the FEL pulse. The purification of spectral and temporal distributions occurs via the reiterated amplification of the best SASE spike.

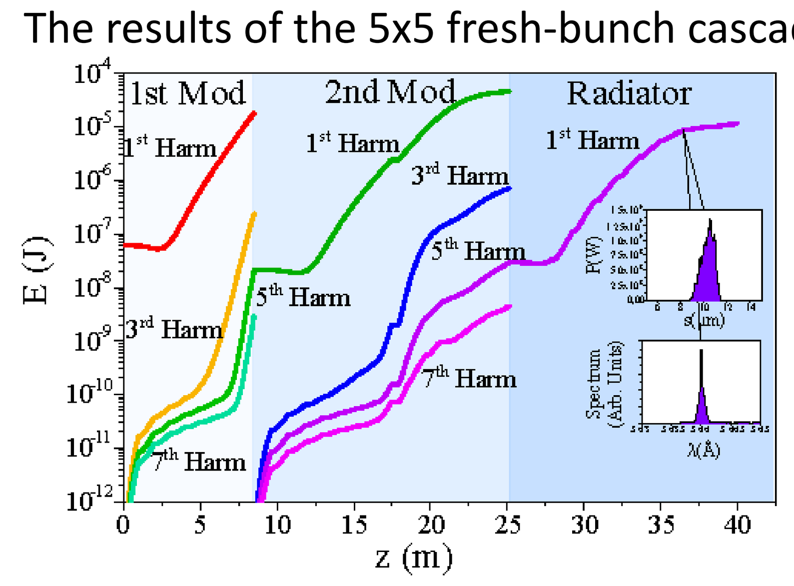
FELO seed, after about 100 cycles

λ	13.6 nm	E	50 nJ
N/shot	3.4×10^9	N/s	1.7×10^{15}
bw	0.15%	rms length	2 μm
div	85 μm	size	100 μm



Reflectance of the Mo/Si mirror as function of wavelength for one mirror (R) and four mirrors (R4), compared with first passage SASE oscillator spectrum and seeded spectrum at saturation. Incidence angle: 3 degrees from the normal.

The results of the 5x5 fresh-bunch cascade with the seed provided by the FELO are presented:



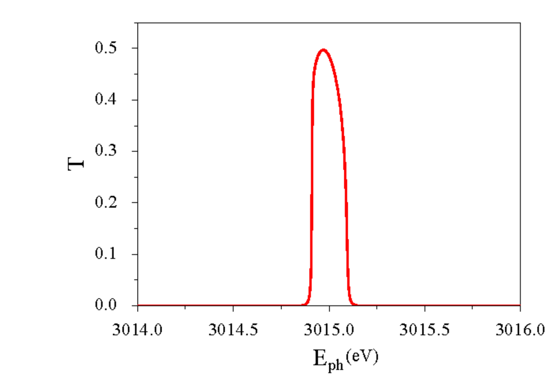
Characteristics of the radiation yield from the FELO-seeded cascade.
The repetition rate of the source is 0.5 MHz.

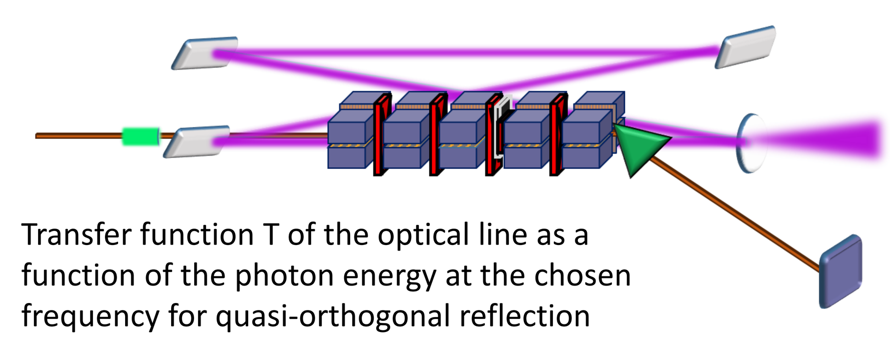
λ	5.44 Å	E	11 μJ
N/shot	3×10^{10}	N/s	1.5×10^{16}
bw	0.017%	rms length	2 μm
div	3.6 μm	size	24 μm

FEL energy of fundamental and harmonics generated in the various modules are presented vs the coordinate z in the undulator. In the boxes, the temporal and spectral distrubution of the pulse.

X-FEL oscillator

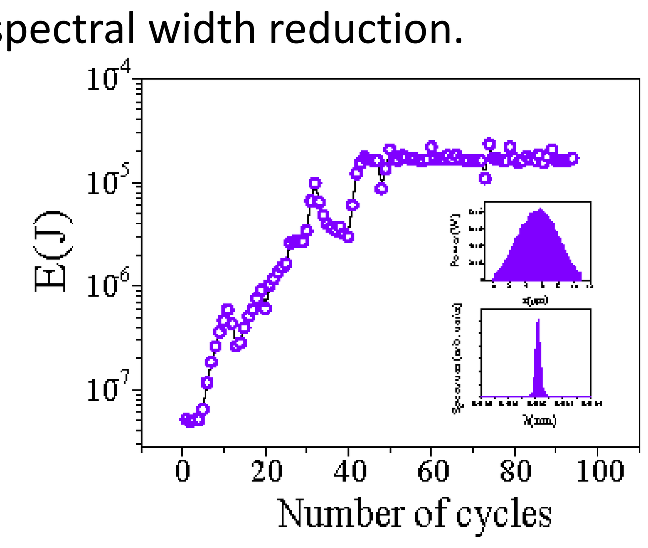
The third option analyzed is an X-FEL oscillator (XFELO) [9,10], where the sequence of the beam packets entering the undulator is synchronized with the radiation reflected and recirculated by hard X-rays mirrors and a beam splitter.





Transfer function T of the optical line as a function of the photon energy at the chosen frequency for quasi-orthogonal reflection

The cavity contains three diamond mirrors and one beam splitter, operating at 4.17 Å.
In this case, the transfer function is much narrower than the natural FEL spectral line and the spectral filtering of the mirrors is the dominant effect in the spectral width reduction.



Radiation yield from XFELO.
The repetition rate of the source is 1MHz.

λ	4.16 Å	E	21 μJ
N/shot	4.4×10^{10}	N/s	4.4×10^{16}
bw	0.4%	length	5 μm
div	14 μrad	size	38 μm

Here the growth of the intracavity energy as function of the round trip number is shown.

Conclusions

The three schemes have been successfully simulated and show the possibility of generating statistically stable X-rays, enabling pump-probe methods at 10-100fs accuracy and with high statistics: the final yield is a radiation pulse with an energy of tens of µJ and a rms length of about 1µm, giving a number of photons per shot of about $10^9 - 10^{10}$ with a rep rate between 0.5 and 1 MHz.

- All seeding schemes based on laser harmonics are difficult to implement at rep rates larger than 100 kHz, due to the insufficient laser pulse energy at increasing rep rates, impeding the seeding process.
- The FELO-based seeding allows to reach higher rep rates but still requires a cascade configuration.
- The X-FELO scheme relies on a much simpler undulator structure, but the X-ray cavity and transport may be a concern.

References

[1] L. Serafini et al., MariX Conceptual Design Report, http://www.sica.unimi.it/ecm/home/ricerca/marix (2019)
[2] L.Serafini et al., NIM A 930 167-172 (2019)
[3] S. Reiche NIM A 429, 243 (1999).
[4] L. Giannessi et al. PRL 108, 164801 (2012)
[5] G Lambert et al., New Journal of Physics 11, 083033 (2009)
[6] S. Schröder et al., Optics Express, 15, 13997
[7] Q. Huang et al., Optical Society of America 22 (16), (2014)
[8] A.A. Zameshin et al., Angular and spectral bandwidth of EUV multilayers near spacer material absorption edges, https://ris.utwente.nl/ws/portalles/portal/67308402/Zameshin
[9] K. J. Kim, Y. Shvyd'ko , and S. Reiche PRL 100, 244802 (2008)
[10] Z. Huang et al., PRL 86, 144801 (2006)