ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP083

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ENERGY SPREAD IMPACT ON HGHG AND EEHG FEL PULSE ENERGY

S. Spampinati†, E. Allaria, L. Giannessi[1], P. Rebernik Ribic[2],
Elettra - Sincrotrone Trieste S.C.p.A., Basovizza, Trieste
[1]also at ENEA C.R. Frascati, Rome, Italy
[2]also at University of Nova Gorica, Nova Gorica, Slovenia

Abstract

VUV and X-ray free electron lasers (FELs) require a very bright electron beam. Seeded FEL harmonic generation is particularly sensible to energy spread and slice energy spread can limit the highest harmonic conversion factor at which coherent radiation can be produced. Different cascade schemes can have different sensibility to the slice energy spread. At FERMI we have evaluated the impact of the slice energy spread on the performance of high gain harmonic generation (HGHG) and of echo enable harmonic generation (EEHG) by measuring the FEL pulse energy as function of the electron beam slice energy spread. The measurements were done at different harmonics. The slice energy spread was varied trough the laser heater located in the linac that drives FERMI.

INTRODUCTION

Facility based on X-ray and VUV free electron lasers (FELs) [1-7] permits to perform a wide class of experiments in physics and chemistry with implications in other fields such as biology.

Most of the existing FEL facilities [1, 2, 4-7] rely on the Self Amplified Spontanous Emission requiring a very bright electron beam characterized by high density in the 6-dimensional phase space implying high current, low transverse emittance and low energy spread [8]. Sensitivity to the energy spread is enhanced for seeded FELs [3]. The high current required by the FEL is obtained compressing the beam in one or more magnetic chicanes. Several collective effects can develop in the linac and in the bunch compressors spoiling the final beam quality and particular techniques have to be used to counteract these effects. Longitudinal microbunching instabilities MBI is one of the most relevant collective effect that can spoil the electron beam quality and the FEL performance [9].

To counteract MBI, linacs used to drive FELs are usually equipped with a laser heater located in the injector [10-12]. The laser heater consists of a short undulator located in a magnetic chicane where an external infrared laser pulse interacts with the electron beam. The increased energy spread can be adjusted to the right level to smear the density modulation in the bunch compressor and then dumping the MBI. Control of MBI and energy spread is particularly important for those seeded schemes based on frequency up conversion mechanisms used to produce highly coherent radiation at an harmonic of the seed.

In High gain harmonic generation (HGHG) [13, 14] an external laser is used to modulate the electron beam energy in a first undulator. This periodic energy modulation at the seed laser wavelength is then converted to current modulation, containing components at the harmonics of the seed. The bunched beam is then injected in a second undulator, tuned at one of the harmonics of the seed, where the coherent emission starts and is amplified by the FEL process. In order to produce a significant bunching the induced energy modulation has to overcome the natural slice energy spread of the beam, at the same time the final energy spread has to be small enough to allow FEL amplification. This makes the scheme very sensitive to energy spread and limit the maximum number of harmonic conversion to slightly more than 10.

A new seeded mechanism call echo enable harmonic generation (EEHG) was proposed [15, 16] and demonstrated on test facilities [17-19]. Recently EEHG has been extended in the soft x-ray down to 5nm in a series of tests done at FERMI [20].

In this work we report measurements performed during the EEHG experiment at FERMI aimed at evaluating the impact of the slice energy spread on the performance of EEHG. The experiment rely on measurements of the FEL pulse energy as function of the electron beam slice energy spread. The measurements were done at different harmonics. In several cases the behaviour of EEHG as a function of the slice energy spread has been compared with similar measurements done with the same beam using the HGHG scheme. The slice energy spread was varied trough the laser heater and the FEL properties were characterized using few different kind of detectors.

HGHG AND EEHG AT FERMI

The FERMI user facility is based upon two externally seeded FELs and covers the extreme ultraviolet (FEL-1) [3] and soft x-ray (FEL-2) [17]. Figure 1a shows the layout of FEL-2 line. FEL-2 is composed of two stage each one working according to the HGHG scheme described above. The seed of the first stage is provided by an external seed while the output of the first stage is used as seed for the second stage. The electron beam coming from the first stage is delayed by a magnetic chicane before entering in the second stage. The electron beam modulation in the second modulator and the FEL emission in the second stage occur now in a fresh part of the electron beam. Figure 1b shows EEHG scheme implemented in FEL-2 line [20]. The first dispersive section is switched off and the undulator segments of the first radiator are opened at a large gap to provide an almost null field on the axis. In the first modulator, the e-beam energy is modulated by the interaction with the first seed laser, as in HGHG. The

† simone.spampinati@elettra.eu

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP083

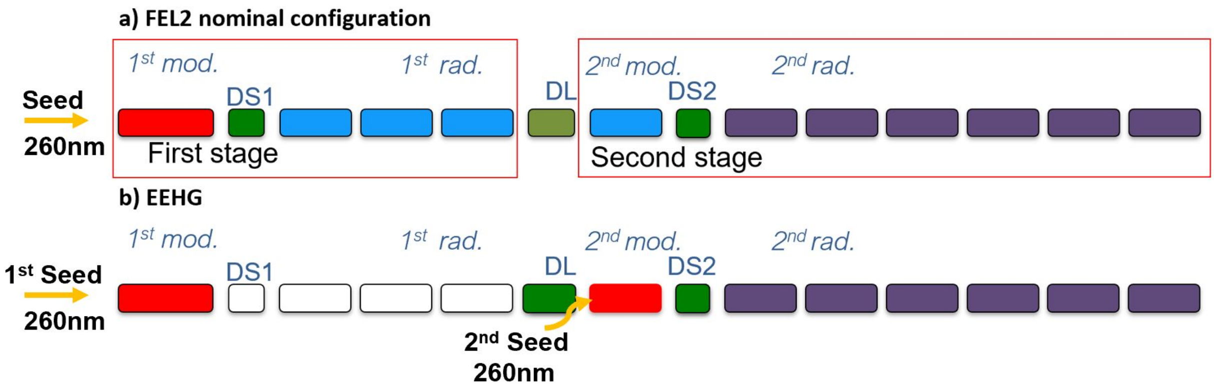

Figure 1: a) nominal layout of FEL-2. b) EEHG implemented at FERMI.

current of the magnetic delay line is increased to provide a sufficiently high dispersion (r56~2 mm). After passing through this strong dispersive section, the portion of the longitudinal e-beam phase space that interacted with the seed is strongly modified resulting in a series of stripes characterized by a reduced energy spread. The beam goes to a single stage of HGHG where the seed is provided by a second UV laser. Both seeds in this case interact with the same part of the beam. Due to the reduced slice energy in each stripe, it is possible to produce a significant bunching with a single stage at very high harmonics of the seed using a moderate energy modulation provided in the second modulator.

As a result of the preparation of phase space before entering the second modulator, EEGH is expected to tolerate larger energy spread. Particularly in EEHG the slice energy spread is expected to have a smaller impact in the degradation of the harmonic bunching with respect to HGHG. The bunching at the harmonic a_E can be espressed, following the notation in [18] as:

$$(1)\quad b_{n,m} = e^{-\frac{\xi_E^2}{2}} J_n(-\xi_e A_1) J_m(-a_E A_2 B_2)$$

where the normalized laser modulations are $A_{1,2} = \frac{\Delta E_{1,2}}{\sigma_E}$ and the normalized dispersion are $B_{1,2} = \frac{K R_{56}^{1,2}}{E}$. σ_E is the slice energy spread, and E is the beam energy. The EEHG scaling factor has been defined as $\xi_E =$ nB_1+$a_E B_2$. In our case both seed laser have the same k vector and the harmonic number is $a_E = n + m$.

During the EEGH experiments done at FERMI we had the possibility to verify the minor sensitivity of EEHG to energy spread with respect to HGHG. Figure 2 shows the behaviour of FEL intensity, both in HGHG and EEHG, as a function of the energy of the laser that drive the laser heater.

Figure 2a shows the FEL pulse energy at 14.7nm, corresponding to the 18th harmonic of the seed (e-beam energy 0.9 GeV), as function of the laser heater energy. The red curve is referred to the HGHG. As previously demonstrated a very small level of heating is enough to supress the microbunching and to improve the FEL performances in the HGHG setup. Increasing the LH energy above the optimum value, needed to suppress the microbunching, drops the FEL power because the increased energy spread and the reduced bunching efficiency. The blue curve shows the behaviour of the EEHG tuned at the same wavelength. We can see that the optimum FEL energy is obtained for a greater value of the laser energy compared to the HGHG case. Our current explanation of this effect is related to the bigger dispersion of the delay line used for EEHG that increases the microbunching gain and consequently more heating from the laser heater is required to suppress MBI and optimize the energy spread at the second dispersion section where the harmonic bunching is produced. Then the FEL remain constant even increasing the laser heater energy by a big factor. Figure 2b shows the same measurement done with the FEL tuned at 8.6 nm corresponding to the 30th harmonic of the seed (e-beam energy 1.1 GeV). In this case the power of EEHG starts to decrease for a laser heater energy double respect to the optimum value. At higher electron beam energy (and lower R56 on the first chicane) the MBI is reduced and hence the optimum for the LH intensity is lower.

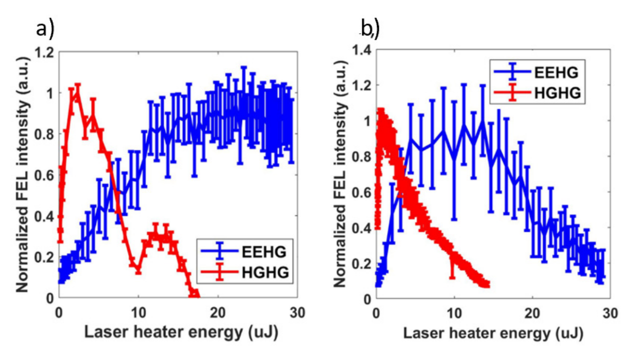

Figure 2: a) FEL energy vs laser heater energy at harmonic 18th . b) FEL energy vs laser heater energy at harmonic 30th.

We can see that the optimum FEL energy is obtained for a greater value of the laser energy in the case of the lower harmonic. The measurements at the 18th harmonic were taken with an electron beam of 0.9GeV and 1.1GeV respectively for the 18th and 30th harmonic. Probably the electron beam was affected by a stronger microbunching at lower energy requiring more energy spread by the laser

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP083

heater. From the theoretical equation for energy spread provided by the laser heater [10] and from experimental measurement with the deflector we have that the minimum energy spread that optimize the FEL emission is 240 kev at H18 and 200 keV at H30.

Figure 2 shows that the sensitivity to the energy spread increases with the harmonic number both in the HGHG configuration and in EEHG. This behaviour is expected and can be derived from the equations for the harmonic bunching. In Fig. 3 we plot the EEHG bunching obtained from eq. (1) as function of the energy spread at the two harmonics.

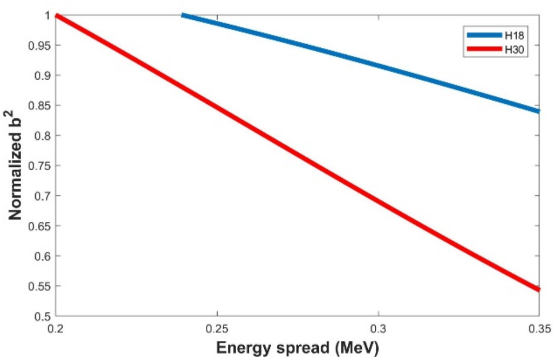

Figure 3: Theoretical normalized square of the bunching calculated for H18 and H30.

The measurements reported in Fig. 2 were taken with all the parameters optimized to have the maximum pulse energy. It is possible to further reduce the sensitivity of EEHG to the energy spread tweaking the value of the second energy dispersive section. Indeed, from eq. 1 it is possible to show that ξ_E governs the formation of the bunching and is always convenient to minimize $|\xi_E|$ and to have a value of n small and negative.

For small value of $|\xi_E|$ the ratio of the dispersions is approximately equal to the harmonic number $a_E \approx \frac{nB_1}{B_2}$ and the effect of the energy spread on the bunching is reduced. From the exponential term in eq. 1 we can see that there is no impact of the energy spread on the bunching for $|\xi_E| = 0$. However, this case the bunching is 0. The bunching and his sensitivity to energy spread grow increasing the value of $|\xi_E|$ towards his optimum value. We have studied the different sensitivity of the FEL energy to the energy spread for different value of $|\xi_E|$. During the experiment we fixed the value of R^1_{56} and we hanged the value of $|\xi_E|$ by changing the value of R^2_{56}. The measurements were repeated for several harmonic of the seed laser. The results reported in Fig. 4 and Fig. 5 are referred to the 30th harmonic of the seed.

Figure 4 shows the FEL energy as function of the value of the R^2_{56} (blue curve) with the expected behaviour of the bunching. The three points indicate the value of R^2_{56} for which we took the measurement reported in Fig.5. The green curve shows the scaling function as function of the value of the of R^2_{56}.

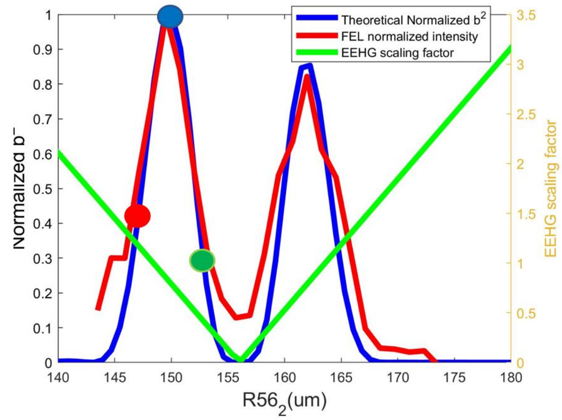

Figure 4: Normalized theoretical square bunching (blue), measured normalized FEL intensity (red) and) EEHG scaling factor (green)vs R56 of the second dispersion section.

Figure 5a shows the FEL energy as function of the laser heater energy for the three values, indicated by three dots in Fig. 4, of R56 of the second chicane around the left peak of the blue and red curves in Fig. 4. Figure 5b shows the expected behaviour of the bunching vs the energy spread for the three same values of R56. The expected behaviour of the sensitivity to the energy spread as function of the EEHG scaling function is confirmed.

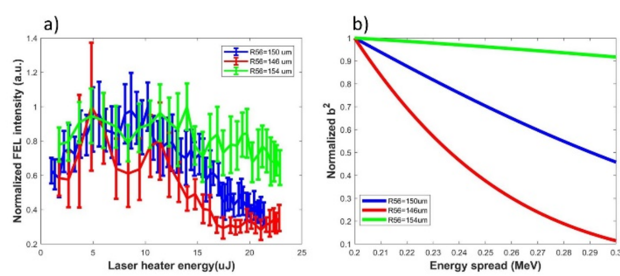

Figure 5: a) FEL intensity vs. laser heater energy. b) Theoretical b^2 vs. energy spread.

CONCLUSIONS

We have evaluated the impact of the slice energy spread on the performance of high gain harmonic generation (HGHG) and of echo enable harmonic generation (EEHG) by measuring the FEL pulse energy as function of the electron beam slice energy spread. EEHG confirms to be less effected by the slice energy respect to HGHG.

REFERENCES

[1] W. Ackermann *et al.*, "Operation of a free-electron laser from the extreme ultraviolet to the water window", *Nat. Photon.* vol. 1, 336–342 (2007). doi:10.1038/nphoton.2007.76

[2] P. Emma *et al.,* "First lasing and operation of an angstrom-wavelength free-electron laser." *Nat. Photon.*, vol. 4, 641–647 (2010). doi:10.1038/nphoton.2010.176

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP083

[3] E. Allaria *et al.*, "Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultra-violet", *Nat. Photon*., vol. 6, 699 (2012). doi:10.1038/nphoton.2012.233

[4] T. Ishikawa *et al.*, "A compact X-ray free-electron laser emitting in the sub-angstrom region", *Nat. Photon*, vol. 6, 540–544 (2012). doi:10.1038/nphoton.2012.141

[5] E. Allaria *et al.*, "Two-stage seeded soft-X-ray free-electron laser", *Nat. Photon*., vol. 7, 913 (2013). doi:10.1038/nphoton.2013.277

[6] H.-S. Kang *et al.* "Hard X-ray free-electron laser with femtosecond-scale timing jitter". *Nat. Photon.*, vol. 11, 708–713 (2017). doi:10.1038/s41566-017-0029-8

[7] SwissFEL, https://www.psi.ch/en/swissfel/about-swissfel

[8] S. Di Mitri, "On the Importance of Electron Beam Brightness in High Gain Free Electron Lasers", *Photonics,* vol. 2, 317-341 (2015). doi:10.3390/photonics2020317

[9] E. Saldin, E. A. Schneidmiller, M. V. Yurkov, "Klystron instability of a relativistic electron beam in a bunch compressor",. *Nucl. Instrum. Methods Phys. Res. Sect. A*., vol. 490, 1–2 (2002). doi: 10.1016/S0168-9002(02)00905-1

[10] Z. Huang *et al.*, "Measurements of the linac coherent light source laser heater and its impact on the x-ray free-electron laser performance", *Phys. Rev. Spec. Top. - Accel. Beams,* vol. 17, 13, 020703 (2010). doi:10.1103/PhysRevSTAB.13.020703

[11] S. Spampinati, *et al.*, "Laser heater commissioning at an externally seeded free-electron laser", *Phys. Rev. Spec. Top. - Accel. Beams,* vol. 17, 120705 (2014). doi:10.1103/PhysRevSTAB.17.120705

[12] E. Ferrari, *et al*., "Impact of Non-Gaussian Electron Energy Heating upon the Performance of a Seeded Free-Electron Laser", *Phys. Rev. Lett.*, vol. 112, 114802. (2014). doi:10.1103/PhysRevLett.112.114802

[13] L. H. Yu, "Generation of intense UV radiation by subharmoni-cally seeded single-pass free-electron lasers". *Phys. Rev. A*, vol. 44, 5178–5193 (1991). doi:10.1103/physreva.44.5178

[14] L. H. Yu *et al.*, "High-Gain Harmonic-Generation Free-Electron Laser", *Science*, vol. 289 (2000), 932-934. doi:10.1126/science.289.5481.932

[15] G. Stupakov, "Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation", *Phys. Rev. Lett.*, vol. 102 (2009), 074801. doi:10.1103/PhysRevLett.102.074801

[16] D. Xiang, G. Stupakov, "Echo-enabled harmonic generation free electron laser", *Phys. Rev. Spec. Top.- Accel. Beams*, vol. 12, 30702 (2009). doi:10.1103/PhysRevSTAB.12.030702

[17] D. Xiang *et al.*, "Demonstration of the Echo-Enabled Harmonic Generation Technique for Short-Wavelength Seeded Free Electron Lasers", *Phys. Rev. Lett.*, vol. 105, 114801 (2010). doi:10.1103/PhysRevLett.105.114801

[18] Z. T. Zhao *et al.*, "First lasing of an echo-enabled harmonic generation free-electron laser", *Nat. Photon.*, vol. 6, 360–363 (2012). doi:10.1038/nphoton.2012.105

[19] E. Hemsing *et al.*, "Echo-enabled harmonics up to the 75th order from precisely tailored electron beams" *Nat. Photon.*, vol. 10, 512–515 (2016). doi:10.1038/nphoton.2016.101

[20] E. Allaria, "First Lasing of a Free Electron Laser in the Soft X-Ray Spectral Range with Echo Enabled Harmonic Generation", presented at the FEL'19, Hamburg, Germany, (2019), paper MOA02, this conference.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI