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ACCURATE CONTROL OF SEED AND FREE-ELECTRON LASER CHIRP WITH BUNCHING SPECTRAL ANALYSIS

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Abstract

The spectro-temporal characteristics of free-electron laser (FEL) radiation emerging from external seeding schemes such as high-gain harmonic generation are shaped by the properties of the initial seed laser. Accurate control of the seed laser envelope and phase is essential to allow for precise manipulation of the FEL output. Based on experimental data obtained at the seeded FEL user facility FERMI, it is shown that detailed bunching spectral analysis enables monitoring of the seed and FEL frequency chirp. The bunching model is extended to be capable of also reproducing the FEL power.

INTRODUCTION

High-Gain Harmonic Generation (HGHG) [1,2] describes an external seeding scheme that makes use of a modulator and a magnetic chicane to pre-bunch the electron beam before sending it to the actual undulators of the Free-Electron Laser (FEL), making the generation of short wavelength, high intense and longitudinal coherent radiation possible. The modulator is an undulator in which the electron bunch is modulated in energy by interacting with a seed laser. In the longitudinal dispersive chicane, this energy modulation is then transformed to a density modulation containing higher harmonics of the seed laser wavelength, which is finally amplified in the subsequent undulators of the FEL, so-called radiators. HGHG is in operation at the FERMI FEL in a single- and double-stage setup to provide longitudinal coherent radiation in the extreme ultraviolet and soft X-ray regime [3, 4]. Based on a comparison of theoretical and experimental FEL spectra as a function of the dispersive strength of the chicane, it has been demonstrated that this seeding scheme allows to control the FEL frequency chirp by adjusting the seed laser phase [5].

In the following, spectra obtained with different frequency chirp of the seed laser are presented and compared with the existing theory. A comparison with measurements of the pulse energy finally suggests that this theory should be extended to take the power gain process and saturation effects in the radiator into account.

THEORY

In the modulator of the HGHG section, the seed laser induces an energy modulation $\Delta E(t)$ along the electron bunch that is usually a multiple of the rms energy spread σ_E. It is therefore common to define a dimensionless energy modulation amplitude, $A(t) = \Delta E(t)/\sigma_E$. The dispersive strength of the bunching chicane is analogously described by a dimensionless parameter, $B = R_{56} k_s \sigma_E / E_0$, with the longitudinal dispersion R_{56} of the chicane, the average electron beam energy E_0 and the wavenumber $k_s = 2\pi/\lambda_s$ of the seed laser. According to [5], the time-dependent bunching factor at the harmonic h can be calculated by

$$b_h(t) = e^{-\frac{1}{2}h^2B^2} J_h(-hBA(t))\, e^{ih[\phi_s(t)+\phi_e(t)]}, \tag{1}$$

where J_h is the Bessel function of the first kind of order h, and $\phi_s(t)$ and $\phi_e(t)$ describe potential phase variations of the seed laser and electrons, respectively. A time-dependent energy profile $E(t)$ of the electron beam, e.g. originating from the RF cavity, can be taken into account by setting

$$\phi_e(t) = (B/\sigma_E)\, E(t)\,. \tag{2}$$

A linear frequency chirp of the seed laser can be considered by defining

$$\phi_s(t) = (\alpha/2)\, t^2\,, \tag{3}$$

whereby also higher order terms can be included, but are not considered here. The energy modulation amplitude $A(t)$ is proportional to the square root of the seed laser power. For a Gaussian laser pulse it can thus be described by

$$A(t) = A \cdot \sqrt{\exp\left(-8\ln(2)\, t^2/(2\tau^2)\right)}\,, \tag{4}$$

where A is the peak value and τ the pulse duration of the seed, here given as the full-width at half maximum (FWHM) causing the $8\ln(2)$ factor.

When an optical element introduces Group Delay Dispersion (GDD), the seed pulse will be stretched by a factor x compared to its nominal value, $\tau = x \cdot \tau_0$, and the energy modulation amplitude will decrease as $A = A_0/\sqrt{x}$. The chirp parameter α is related to the GDD by

$$\mathrm{GDD} \cdot \Delta\omega^2 = \alpha \cdot \tau^2\,. \tag{5}$$

A relation between the chirp parameter, the FWHM pulse duration τ and the bandwidth $\Delta\omega$ is given by [6]

$$\Delta\omega \cdot \tau = \frac{8\ln(2)}{2} \cdot \sqrt{1 + \left(2\alpha\tau^2/(8\ln(2))\right)^2}\,. \tag{6}$$

When assuming a fixed laser bandwidth, it is determined by the transform-limited pulse duration, $\Delta\omega = 8\ln(2)/(2\tau_0)$, such that

$$x = \sqrt{1 + \left(\frac{\mathrm{GDD} \cdot 8\ln(2)}{2\tau_0^2}\right)^2}\,. \tag{7}$$

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Together with Eq. (5), this allows to express the quadratic phase in Eq. (3) in terms of GDD and transform-limited pulse duration:

$$\phi_s(t) = \frac{\mathrm{GDD}}{\frac{\tau_0^4}{8\ln(2)^2} + 2\mathrm{GDD}^2} \cdot t^2\,. \qquad (8)$$

With this, information about the final FEL spectrum can be obtained by performing a Fourier transform of $b_h(t)$ and calculating $|b_h(k)|^2$ since the FEL power scales as $P \propto |b|^2$.

SPECTRAL ANALYSIS

The experimental data were obtained in the first stage of FEL 2 at FERMI by sending an electron beam with an average energy of 1.418 GeV through an HGHG setup to achieve bunching at the $h = 6$th harmonic of a seed laser wavelength of 255 nm, which is then amplified in 3 helical radiator modules, each of 2.42 m length. The amount of GDD introduced to the seed laser pulse is adjusted with a single pass compressor. In compressed mode, a pulse duration of about $\tau_0 = 85$ fs was measured. The GDD values expected for different compressor settings are used in the theoretical model to reproduce the experimental spectra. The resulting pulse stretch agrees well with measured pulse durations and Fig. 1 shows an excellent agreement with the measured spectra as a function of the chicane R_{56} for different GDD values. The electron bunch is assumed to have a quadratic energy chirp of $\chi_2 = 26\,\mathrm{MeV/ps}^2$, where $E(t) = E_0 + \frac{1}{2}\chi_2 t^2$, and the additional longitudinal dispersion due to the modulator (30 periods) is taken into account in the theoretical approach. All parameters are kept fixed except the GDD and accordingly the seed duration and energy modulation amplitude. As already reported in [5], it is evident that the simple theoretical approach based on Eq. (1) can reproduce the splitting of the spectrum due to electron overbunching with increasing R_{56} by considering both laser and electron chirp. However, the features in the normalized spectra in Fig. 1 do not allow to determine the variation in FEL pulse energy with changing R_{56} and are not suited for determining absolute values of A and σ_E since the argument of the Bessel function in Eq. (1) only depends on the product $\Delta E = A\sigma_E$.

PULSE ENERGY AND POWER GAIN

Figure 2 shows the normalized pulse energy as a function of R_{56}, belonging to the data set presented in Fig. 1a. The experimental data obtained from a calibrated gas detector as well as by integrating the signal of the spectrometer are both in good agreement. Theoretical data are calculated by integrating the modeled spectrum, that is $|b(k)|^2$. However, the bunching equation alone is not capable of reproducing the measured data, indicating that additional terms are needed to take into consideration the power growth in the radiator. Experience with similar machine setups show that the energy spread required for an acceptable agreement between theory and experimental data is unreasonable small.

Taking into account the quadratic power growth due to the pre-bunched beam at the beginning of the radiator, the subsequent exponential FEL power gain as well as saturation effects in the later parts of the radiator, the overall power growth can be approximated by [7]

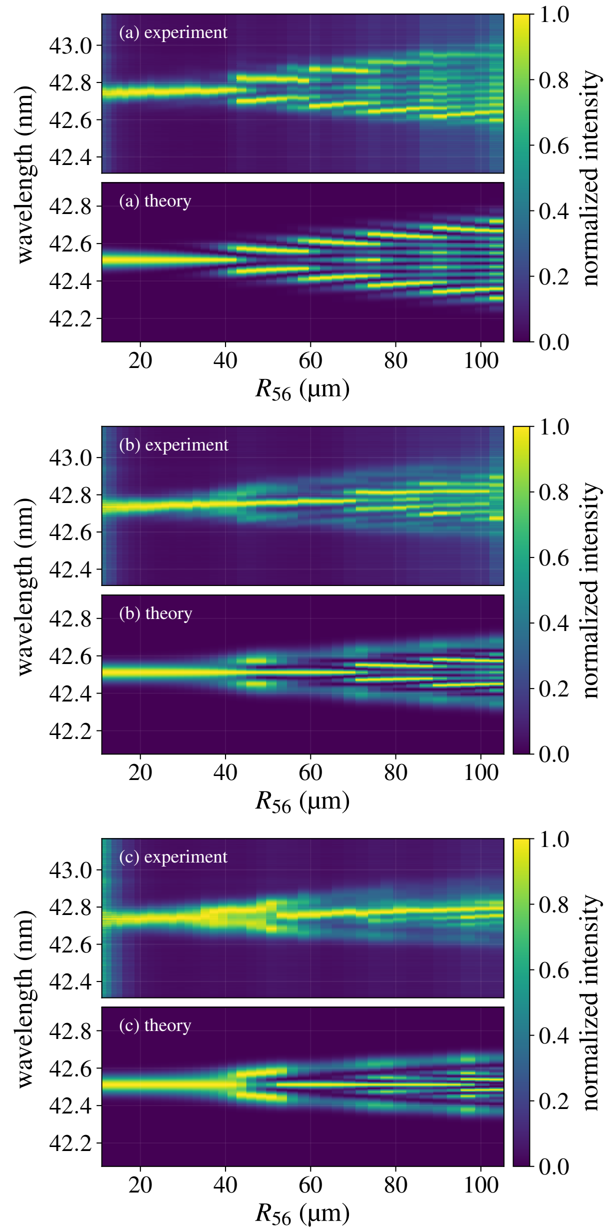

Figure 1: Experimental and theoretical FEL spectrum as a function of the chicane R_{56} for a seed laser of 85 fs transform-limited duration and a GDD of (a) +200 fs^2, (b) −2500 fs^2 and (c) −3800 fs^2. For each R_{56} value, the intensity is normalized and experimental data are averaged over 100 shots. Deviations of the wavelength are likely due to the calibration of the spectrometer and a linear chirp of the electron beam.

$$P(z) = P_{\mathrm{th}} \cdot \left[\frac{\frac{1}{3}\left(\frac{z}{L_g}\right)^2}{1 + \frac{1}{3}\left(\frac{z}{L_g}\right)^2} + \frac{\frac{1}{2}\exp\left(\frac{z}{L_g} - \sqrt{3}\right)}{1 + \frac{P_{\mathrm{th}}}{2P^*_{\mathrm{sat}}}\exp\left(\frac{z}{L_g} - \sqrt{3}\right)} \right]. \qquad (9)$$

Here, $z = 7.26$ m is the distance traveled in the radiator, L_g is the power gain length, $P_{\mathrm{th}} = \rho_{\mathrm{FEL}} \cdot |b|^2 \cdot P_{\mathrm{beam}}$ includes

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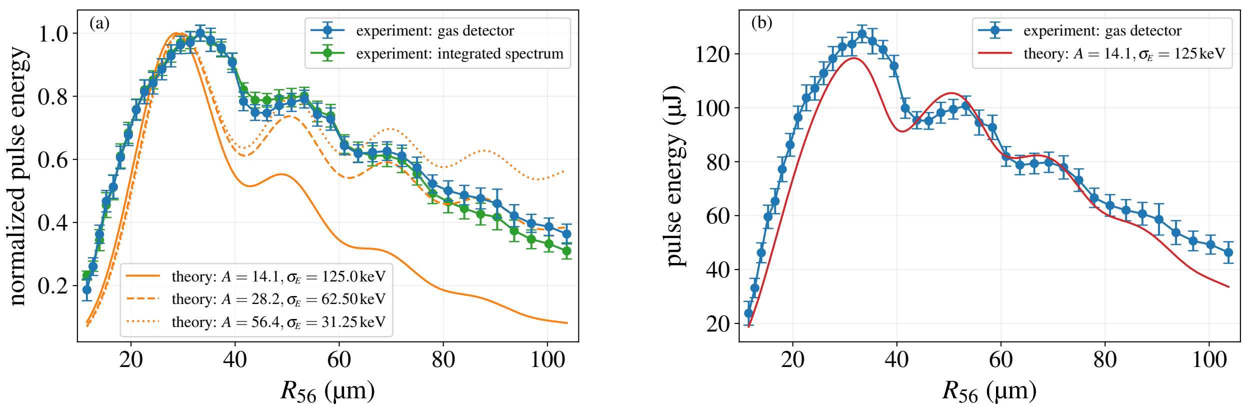

Figure 2: (a) Normalized FEL pulse energy as a function of the chicane R_{56}, corresponding to Fig. 1a. The experimental curves are obtained from a gas detector and the integrated spectrum. The theoretical model based on integration of $|b(k)|^2$ is not sufficient to reproduce these data. (b) The theory is extended by a term describing the power growth in the radiator.

the FEL parameter, the initial bunching and the electron beam power, and $P^*_{\text{sat}} = P_{\text{sat}} - P_{\text{th}}$ is given by the saturation power P_{sat} of the FEL. A temporal description of the power is obtained by making use of the bunching from Eq. (1) and a 3D approximation of the saturation power and gain length [8, 9], which depend on the local beam energy spread $\sigma_A(t) = \sigma_E\sqrt{1 + A(t)^2/2}$ induced by the time-dependent energy modulation amplitude. Additional parameters used in the calculation are the period length $\lambda_u = 5.5$ cm of the radiator, a peak current of 630 A, a normalized emittance of 1 mm mrad and a transverse rms electron beam size of 60 µm. Figure 3 highlights the effect of saturation on the spectral and temporal distributions. Integration of the power over time finally yields the pulse energy, as shown in Fig. 2b. The extended theoretical model results in an improved fit to the measured data and, moreover, provides an absolute value of the pulse energy, which agrees well with the experiment and allows estimations of the electron beam and seed parameters. The spectrum is estimated from the power given by Eq. (9) and the initial bunching phase provided by Eq. (1), and fits well to the spectral features and intensity distribution of the experimental data, as illustrated in Fig. 4.

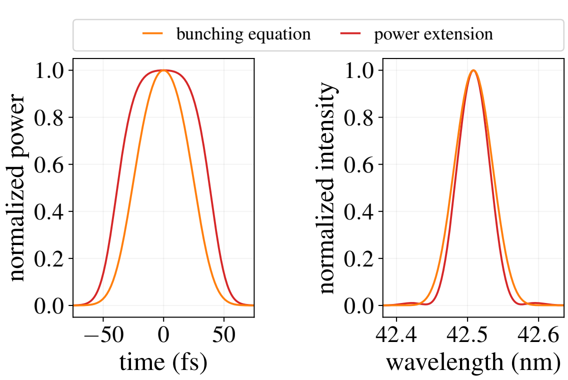

Figure 3: Power and spectral profile at $R_{56} = 20$ µm based on the square of the absolute bunching factor in Eq. (1) and the power approximation in Eq. (9).

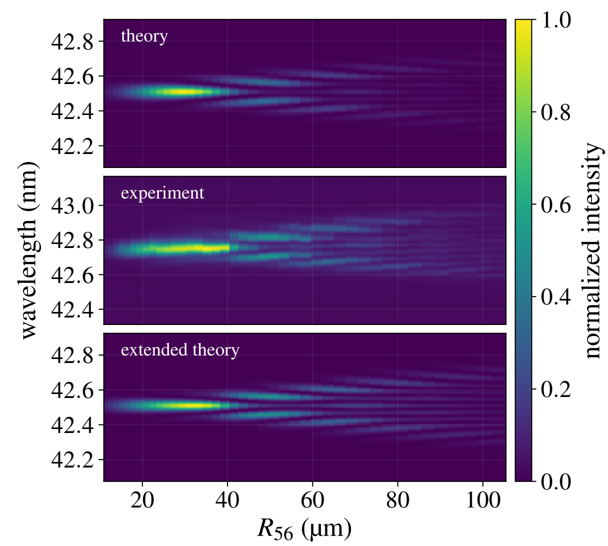

Figure 4: Same as Fig. 1a but intensities are normalized only once to the respective maximum. In addition, the modeled spectrum at the bottom takes the power growth in the radiator into account. In both theoretical approaches it is assumed that $A = 14.1$ and $\sigma_E = 125$ keV.

CONCLUSION

The HGHG bunching model is capable of reproducing spectral features in presence of electron and seed laser chirp. However, measurements of the absolute intensity and pulse energy as a function of the dispersive strength have shown that the existing theory has to be extended by additional terms describing the power growth and saturation effects in the radiator to match the experimental data.

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REFERENCES

[1] L. H. Yu, “Generation of intense uv radiation by subharmonically seeded single-pass free-electron lasers”, *Phys. Rev. A*, vol. 44, pp. 5178–5193, 1991. doi:10.1103/PhysRevA.44.5178

[2] L. H. Yu *et al.*, “High-Gain Harmonic-Generation Free-Electron Laser”, *Science*, vol. 289, pp. 932-934, 2000. doi:10.1126/science.289.5481.932

[3] E. Allaria *et al.*, “Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet”, *Nature Photonics*, vol. 6, pp. 699–704, 2012. doi:10.1038/nphoton.2012.233

[4] E. Allaria *et al.*, “Two-stage seeded soft-X-ray free-electron laser”, *Nature Photonics*, vol. 7, pp. 913–918, 2013. doi:10.1038/nphoton.2013.277

[5] D. Gauthier *et al.*, “Spectrotemporal Shaping of Seeded Free-Electron Laser Pulses”, *Phys. Rev. Lett.*, vol. 115, p. 114801, 2015. doi:10.1103/PhysRevLett.115.114801

[6] J.-C. Diels and W. Rudolph, “Ultrashort Laser Pulse Phenomena - Fundamentals, Techniques, and Applications on a Femtosecond Time Scale (Second Edition)”, *Academic Press*, pp. 1–60, 2006. doi:10.1038/nphoton.2013.277

[7] L. Giannessi, “Seeding and Harmonic Generation in Free-Electron Lasers”, in *Synchrotron light sources and free-electron lasers: accelerator physics, instrumentation and science applications* (Springer Berlin Heidelberg, New York, NY, 2016), vol. 115, pp. 195–223. doi:10.1007/978-3-319-14394-1

[8] M. Xie, “Design optimization for an X-ray free electron laser driven by SLAC linac”, in *Proc. PAC’95*, Dallas, TX, USA, May 1995, paper TPG10, pp. 183-185. doi:10.1109/PAC.1995.504603

[9] M. Xie, “Exact and variational solutions of 3D eigenmodes in high gain FELs”, *Nucl. Instrum. Meth. A*, vol. 445, pp. 59-66, 2000. doi:10.1016/S0168-9002(00)00114-5