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RADIATION SPECTRUM STATISTICS IN A HIGH-GAIN FREE-ELECTRON LASER AT 266 NM

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Abstract

High Gain Harmonic Generation FEL is in operations at the DUV-FEL facility (BNL). During HGHG FEL characterization we have measured a set of data demonstrating basic properties of the FEL radiation and compared them with analytic calculations [1]. This paper describes continuation of characterization of the HGHG FEL radiation output, based on the spectral measurements.

We discuss analysis of an experiment at which the tunability concept of a seeded FEL with a fixed seed wavelength has been verified [2]. During the experiment we recorded about 200 radiation spectra corresponding to different energy chirps in the electron beam. We have analysed this set of spectral data to obtain statistical properties of HGHG radiation. Correlations and trends in the radiation spectrum at 266 nm have been observed and studied.

INTRODUCTION

In [3] we have briefly discussed an experiment on wavelength tuning that took place at the DUV FEL. Relevant DUV FEL parameters are listed in Table 1.

Table 1. DUV FEL parameters

Beam energy, MeV	175
Seed laser wavelength, nm	800
Seed laser Raleigh range, m	2.4
Seed laser peak power, MW	1
Harmonic number	3
Radiator period, m	0.0389
Radiator length, m	10
Modulator length, m	0.8
Modulator period, m	0.08
Maximum R_{56} of DS, mm	-0.34
Intrinsic energy spread (RMS)	$3\cdot10^{-5}$
Bunch length (RMS), ps	0.5
HGHG pulse length (RMS), ps	0.5

In the experiment we varied the phase of the last linac tank (therefore varying the energy chirp), measuring HGHG spectrum for any particular value of the tank RF phase. The value of the central wavelength for the beam without chirp has been measured as 265 nm.

As a result of the experiment we have obtained 176 radiation spectra for 9 different chirps ranging from –13 m^{-1} to +8 m^{-1}.

EXPERIMENTAL DATA ANALYSIS

We have taken about 20 spectra for each particular value of the energy chirp. Spectra were taken in a consecutive manner, i.e. sequence of spectra corresponds to the sequence of the electron bunches at 2 Hz without interruptions. Before processing the spectral data set we analysed temporal trends in the radiation spectra exemplified in Figure 1.

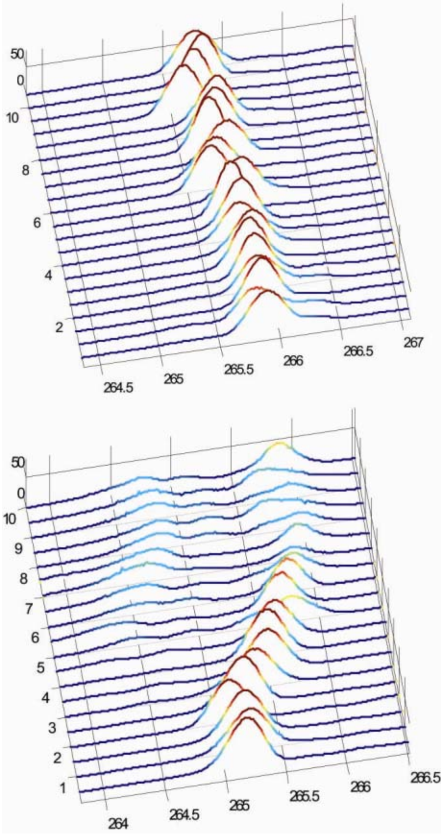

Figure 1: Evolution of the HGHG spectrum over 20 consecutive radiation pulses. Abscissa is scaled in nanometers, ordinate in seconds. Vertical axis corresponds to the spectral intensity in arbitrary units.

In one case (Figure 1, upper plot) central wavelength is stable and its fluctuation is very small and uncorrelated. In the other case (Figure 1, lower plot) we observe central wavelength wandering around its average position with characteristic time of a few seconds. This effect may be caused by instabilities of accelerator components including long-term drifts of the drive laser phase relative to the RF phase. An interesting feature on the Figure 1 is in the modification of the spectral shape for the deviations from the average wavelength that are about 1 nm.

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Spectral shape becomes of a complicated nature and exhibits several maxima located far apart from each other. Figure 1 illustrates this phenomenon in such way that, while spectrum drifts towards longer wavelengths, a satellite appears at 264.5 nm and follows to grow.

Before describing the data analysis we define the spectral parameters as shown on Figure 2. The plot shows an arbitrarily chosen spectrum of the HGHG radiation. Due to the background present in all spectra we use full-width half-maximum (FWHM) value as a measure of spectral bandwidth rather than root-mean-square (RMS) value. Due to an asymmetry of the spectral shape we introduce a peak wavelength, which corresponds to the peak value of the radiation intensity, and the mean wavelength corresponding to the intensity mean value. The area under the spectral curve is a measure of the radiated energy per pulse.

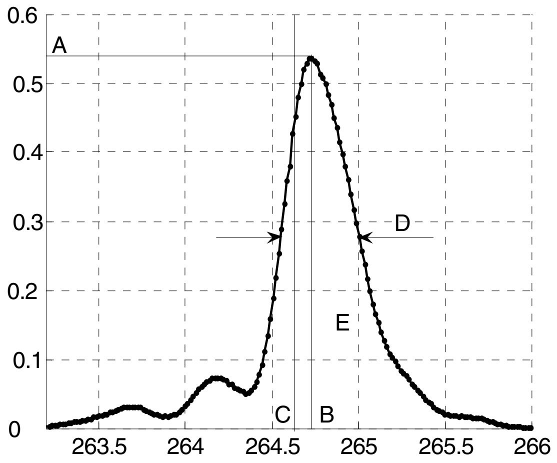

Figure 2: Definition of spectral parameters: A – peak intensity, B – wavelength corresponding to the peak intensity, C – mean wavelength, D – full width half-maximum of the spectral line, E – intensity integral

During the data analysis we have processed all the measured spectra for 9 values of the energy chirp. We plot the dependence of peak and mean wavelengths on the energy chirp in the electron beam (Figure 3). Central wavelength is changing for different energy chirps in accordance with the wavelength tuning principle ([2]). The overall wavelength tuning range is measured of about 1% (from 263.4 nm for -45° to 266.1 nm for 25° in RF phase) and limited by the strength of the dispersion section. The error bars on the plot show uncorrelated jitter of the central wavelength. Using calculated value of the longitudinal dispersion that includes dispersion in the DS (dispersive section) and in the radiator we obtain the compression ratio for every particular value of energy chirp. The linear fit in Figure 3 demonstrates a good agreement with the analytic estimate.

We have performed statistical analysis of the measured data set focusing on the peak spectral intensity and the intensity integral (or area under a spectral curve, see Figure 2).

Since the electron bunch is chirped we plot the dependence of these spectral parameters versus the energy chirp (Figure 4).

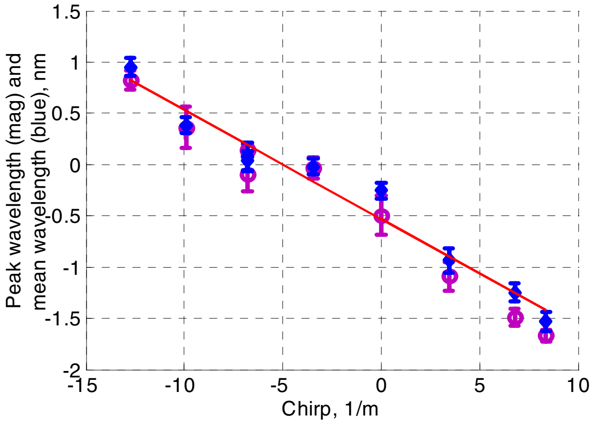

Figure 3: Peak wavelength (magenta) and mean wavelength (blue) versus energy chirp

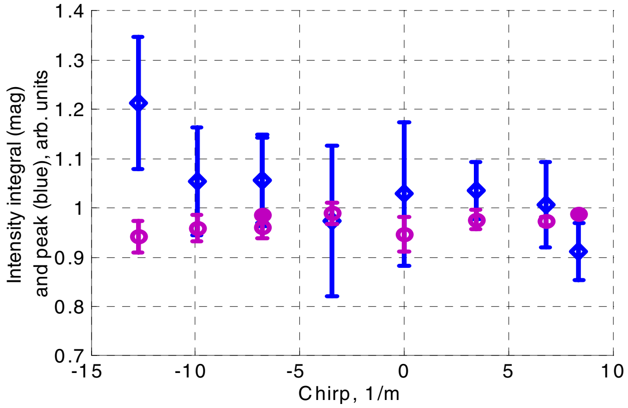

Figure 4: Dependence of intensity integral (magenta) and peak intensity (blue) versus energy chirp

One can see that neither intensity integral nor peak intensity depend on the chirp value. Calculated value of RMS peak intensity fluctuation is about 10%, for intensity integral we get 2.3 %. The latter value demonstrates a high degree of stability of the FEL output.

Since intensity integral exhibits such a high stability, fluctuations of the peak intensity should correlate with the spectral bandwidth (indeed, intensity integral is proportional to a product of these two). This conclusion is confirmed by analysis of the dependences plotted in Figure 5. Peak intensity is found to be inversely proportional (red fit in Figure 5) to the spectral bandwidth. Scattered data points in the lower part of the plot correspond to the spectra with multiple maxima (Figure 1). Even for these spectra the intensity integral is preserved with a high accuracy and the bandwidth-peak intensity correlation still is in order.

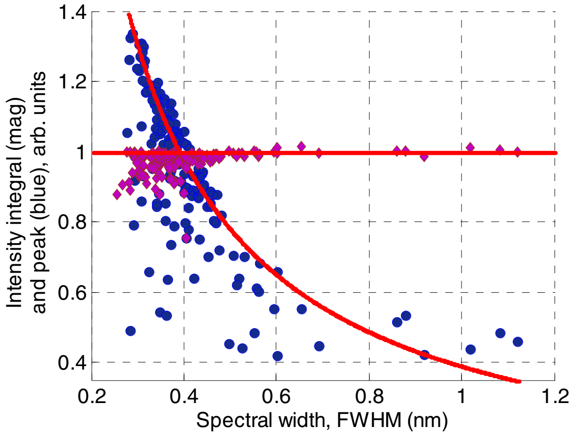

Figure 5: Dependence of intensity integral (magenta) and peak intensity (blue) versus spectral width.

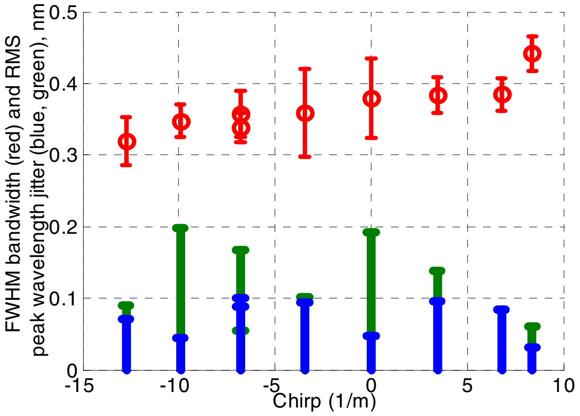

Figure 6: Dependence of FWHM bandwidth (red) and RMS peak wavelength jitter (blue) versus energy chirp in the electron beam. Green bars correspond to the RMS peak wavelength jitter without long-term wavelength drifts (see Figure 1).

Lastly we plot the dependence of the FWHM spectral bandwidth on the energy chirp in the electron bunch (Figure 6). We observe almost no change of the bandwidth with respect to the energy chirp.

Bars in the lower part of plot demonstrate the RMS fluctuation of the central wavelength around its mean value. Green bars correspond to the "raw" data which includes long-term drift can be seen in Figure 6. Potentially these drifts can be removed by implementing a feedback based on the on-line spectral measurements. We approximated long-term drifts of central wavelength by a 3rd order polynomial and subtracted the correlated wander of the central wavelength from the data set spectra for each value of chirp. Blue bars demonstrate residual fast pulse-to-pulse jitter of the central wavelength around its central value. The amount of jitter is much smaller than the spectral bandwidth and independent on the energy chirp in electron beam. We conclude that, using the feedback, the residual jitter in the central wavelength can be made as small as about 25% of the spectral bandwidth.

CONCLUSION

The experiment described in this paper allowed us to characterize spectral properties of radiation from an HGHG FEL. High precision measurements of radiation spectra demonstrate high quality of the output radiation: the pulse energy fluctuations of 2.3 %, peak intensity and FWHM bandwidth fluctuations of 10 %, central wavelength stability as a fraction of the spectral bandwidth.

It is observed that for a large wavelength detuning spectral intensity broadens and undergoes redistribution. We are working now on understanding of this interesting effect.

Wavelength tuning concept has been verified experimentally. We have demonstrated a smooth tuning of the FEL output across the optical spectrum. In our earlier paper [2] we have demonstrated a possibility of making HGHG FEL completely tunable laser in a short-wavelength range.

Implementing a feedback based on spectral measurements of an FEL output can mitigate observed slow drifts of the central wavelength.

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