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FREQUENCY DOUBLING MODE OF OPERATION OF FREE ELECTRON LASER FLASH2

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Abstract

We report on the results of the first operation of a frequency doubler at free electron laser FLASH2. The scheme uses the feature of the variable-gap undulator. The undulator is divided into two parts. The second part of the undulator is tuned to the double frequency of the first part. The amplification process in the first undulator part is stopped at the onset of the nonlinear regime, such that nonlinear higher-harmonic bunching in the electron beam density becomes pronouncing, but the radiation level is still small to disturb the electron beam significantly. The modulated electron beam enters the second part of the undulator and generates radiation at the second harmonic. A frequency doubler allows operation in a two-color mode and operation at shorter wavelengths with respect to standard SASE scheme. Tuning of the electron beam trajectory, phase shifters and compression allows tuning of intensities of the first and the second harmonic. The shortest wavelength of 3.1 nm (photon energy 400 eV) has been achieved with a frequency doubler scheme, which is significantly below the design value for the standard SASE option.

INTRODUCTION

Free electron laser FLASH is equipped with two undulator beamlines [1]. Fixed gap undulator (period 2.73 cm, peak magnetic field 0.48 T, total magnetic length 27 m) is installed in the first beamline, FLASH1. The second beam line, FLASH2, is equipped with variable gap undulator (period 3.14 cm, maximum peak magnetic field 0.96 T, total magnetic length 30 m). With operating range of the electron beam energies of 0.4 - 1.25 GeV FLASH1 and FLASH 2 beamline cover wavelength range from 4 to 52 nm and 3.5 to 90 nm, respectively. Multiple scientific applications will benefit a lot with extension of the operating range of the facility deep into the water window spanning from 4.38 nm and 2.34 nm (K-absorption edges of carbon and oxygen).

One techniques to generate shorter wavelengths is by using the second harmonic afterburner [2–7]. Operating the afterburner at the 2nd harmonic has been tested successfully at LCLS with 5 final undulator modules retuned to the 2nd harmonic [7]. With long, variable gap undulator of FLASH2 it is possible to implement frequency doubler scheme. Here we demonstrate experimental results from FLASH2: with an appropriate optimization of undulator tuning it becomes possible to operate facility at visibly shorter wavelengths and organize two color mode of operation ($\omega + 2\omega$) with controllable radiation pulse intensities.

OPERATION OF FREQUENCY DOUBLER

The undulator is divided into two sections tuned to ω and 2ω frequencies. The plots in Fig. 1 illustrate general features of the operation of the frequency doubling scheme. Black dashed line shows evolution of the radiation power along the ω-section. The amplification process stops at some length, and then electron beam enters the 2ω-section tuned to the doubled frequency. Radiation with frequency ω does not interact with the electron beam in the 2ω-section, and just propagates forward. Radiation power produced in the ω-section at the second harmonic frequency is significantly suppressed [6, 8], thus only the beam density modulations at 2ω frequency can seed the 2ω-section.

We performed simulations of the amplification process for the full parameter space of the lengths of the ω and 2ω sections, and the results are summarized in Fig. 2. Despite the fact that simulations have been performed for specific sets of electron beam parameters, presentation of the results here is in normalized form to allow use of them for a wider range of parameters. The x-coordinate is radiation power is from the ω section normalized to the saturation power of SASE FEL operating at frequency ω. The y-coordinate is radiation power from the 2ω-section normalized to the

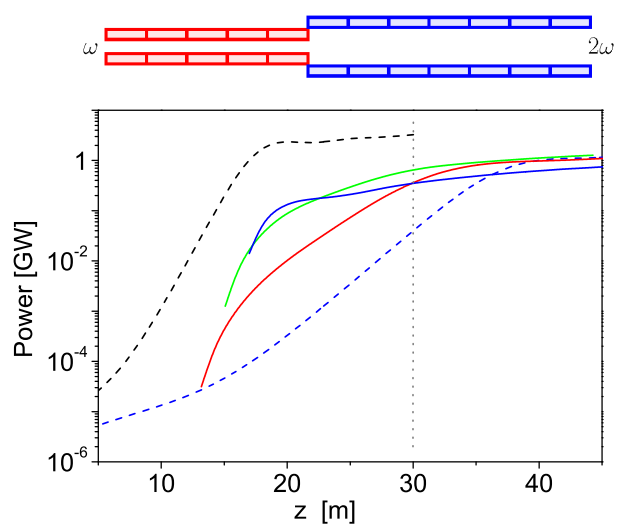

Figure 1: Top: Conceptual scheme of frequency doubler with variable gap undulator. Bottom: Evolution of the radiation power along FLASH2 undulator. Dashed curves correspond to SASE FEL operating at 8 nm (black) and at 4 nm (blue). Solid curves correspond to frequency doubler 8 nm → 4 nm for different lengths of the ω undulator section (red, green, and blue colors). Gray dashed line at z = 30 m shows magnetic length of FLASH2 undulator. Electron energy is 1080 MeV, beam current is 1500 A, normalized rms emittance 1 π mm-mrad, and rms energy spread 0.15 MeV. Simulations have been performed with code FAST [9].

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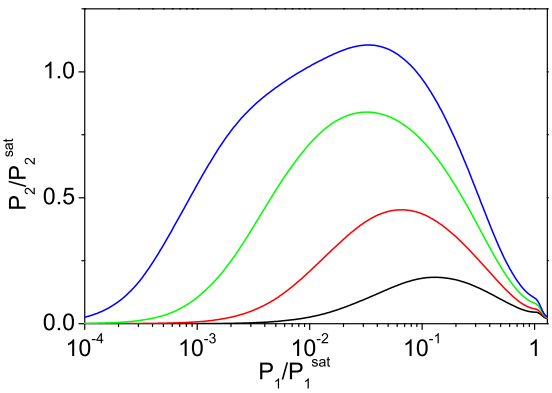

Figure 2: Parameter space of radiation powers from frequency doubler at FLASH2. P_1 is radiation power at ω at the exit of the first section, and P_2 is radiation power at 2ω at the exit of the doubling section. Radiation powers are normalized to the corresponding saturation powers of SASE FEL. Different colors (black, red, green, and blue) denote lengths of the doubling section in terms of the saturation length: 1/6 $z_{\rm sat}$, 1/3 $z_{\rm sat}$, 1/2 $z_{\rm sat}$, and 2/3 $z_{\rm sat}$. Simulations have been performed with code FAST [9].

saturation power of the SASE FEL operating at frequency 2ω. We see that with two-color mode of operation it is possible to produce simultaneously high power at both frequencies with the level of about 20% of the saturation power. When amplification process in the first undulator terminates at the onset of the nonlinear regime, it is possible to generate high radiation power at the second harmonic in the second part of the undulator.

Simple physical considerations explain operation of the frequency doubler. Indeed, for a short length of the ω-section, when the amplification process stays in the exponential gain regime, the beam density modulations at frequency 2ω remain on the level of the shot noise. Induced modulations at the frequency 2ω (and higher harmonics) occur only in the nonlinear stage of amplification. At the onset of nonlinear regime induced modulation at 2ω is small, and gradually grows when amplification process approaches saturation. At the same time we occur degradation of the electron beam quality due to interaction of the electron beam with radiation. Thus, we deal with two competing effects: growth of the beam modulation, and degradation of the electron beam quality. Lucky factor for the frequency doubling scheme is that the growth of the beam density modulation advances the degradation of the beam quality, since the radiation power should be produced first, and only then it interacts with the beam. When amplification process enters the post-saturation regime, the quality of the beam and the beam bunching degrade such that the electron beam becomes to be not appropriate for efficient radiation of higher harmonics.

EXPERIMENTAL RESULTS

Operation of frequency doubler has been successfully demonstrated during several test runs at FLASH2 in 2016. Experiments have been performed at the energy of the electron beam of 1080 MeV and 1230 MeV. Tuning of the frequency doubler scheme with variable gap undulator does not require any special techniques. First, we tune maximum SASE gain in the uniform undulator tuned to frequency ω. Analysis of the gain curve and fluctuations of the radiation pulse energy allows to determine optimum length of the ω-section. Then we tune remaining sections to the frequency 2ω, and after adjustment of the phase shifters and electron beam orbit, the frequency doubler starts to generate radiation at the second harmonic.

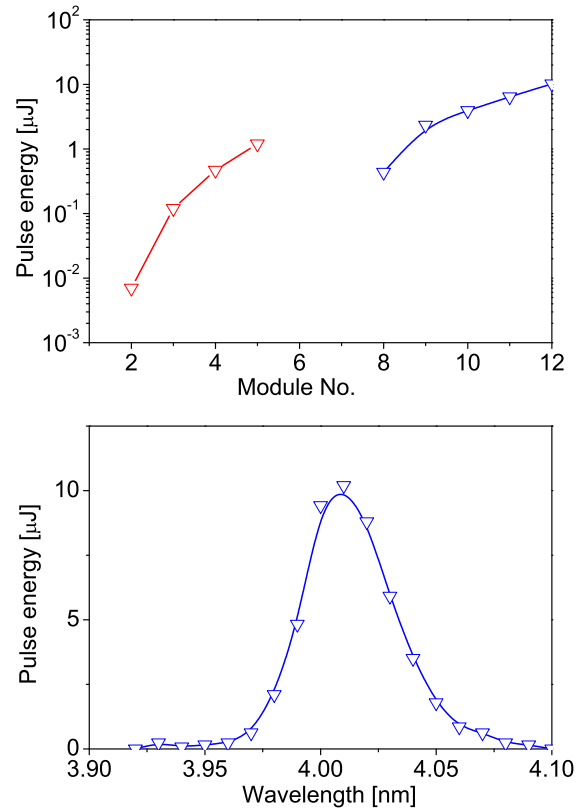

Figure 3: Frequency doubler at FLASH2 (experimental data). Left: gain curve of the frequency doubler at FLASH 2. First part of the undulator (5 modules) is tuned to 8 nm, and second part (7 modules) is tuned to 4 nm. Red and blue color correspond to the radiation wavelength of 8 nm and 4 nm. Right: radiation pulse energy at the 2nd harmonic versus resonance frequency of the second part of the undulator. Electron energy is 1080 MeV, bunch charge is 300 pC.

Figure 3 shows the gain curve of the frequency doubler 8 nm $\rightarrow$ 4 nm. First five undulator sections were tuned to 8 nm, and the last seven sections were tuned to 4 nm. Red and blue curves show radiation pulse energies at 8 nm and 4 nm. Amplification process in the second part (frequency doubler) exhibits resonance behavior on the frequency detuning (right plot in Fig. 3). Even harmonics of the radiation are strongly suppressed in the planar undulator, thus we get confirmation that the beam bunching at the second harmonic seeds the amplification process of the frequency doubling sections. One can compare experimental and simulation results presented in Fig. 1. Gain curves look pretty much similar. As for the resonance curve, the width of experimental curve is significantly wider than FEL parameter ρ. This

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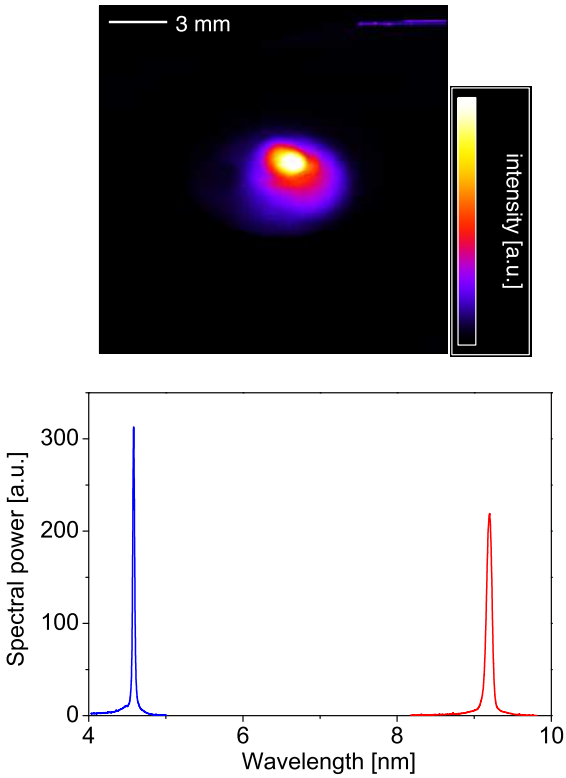

Figure 4: Photon beam image in the experimental hall(top) and radiation spectra (bottom) of the frequency doubler at FLASH2 (experimental data). Small yellow spot is 4.5 nm (2nd harmonic) radiation, pulse energy is 10 J. Larger blue/pink spot is 9 nm radiation, pulse energy is 10 μJ. Electron energy is 1080 MeV, bunch charge is 300 pC.

is typical signature of the energy chirp along the electron beam induced by the beam formation system.

Our experience shows that tuning procedure of the frequency doubler is simple and reproducible. In particular, it is possible to tune relative intensities of two colors (ω, 2ω) in a wide limits. When tuned to equal intensities, pulse energies were in the range from a few to 10 microjoules. Radiation has been transported to FLASH2 experimental hall for characterization. Figure 4 shows an example for photon beam images and spectra of two color mode of operation for the frequency doubler 9 nm $\rightarrow$ 4.5 nm. With this first experience we can state that this operational mode can be proposed to users.

With fixed electron energy, shortening of the radiation wavelength is achieved by opening the undulator gap. Undulator field is reduced, the FEL gain falls down, and starting from some wavelength the undulator length is not sufficient to reach saturation regime. Frequency doubler scheme is capable to generate shorter wavelength radiation than standard SASE FEL. Indeed, the first part of the undulator operates at twice longer wavelength, and saturation is obtained at a half of the full undulator length. Induced beam bunching at the second harmonic is much larger than the shot noise in the electron beam, and it becomes possible to reach saturation on much shorter length of the doubling section. For fair

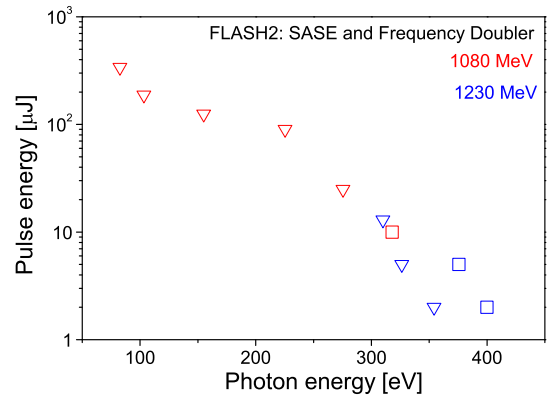

Figure 5: Radiation pulse energy versus photon energy. Experimental data from FLASH2 for electron energy of 1080 MeV and 1230 MeV, bunch charge is 300 pC. Triangles represent SASE, and squares represent frequency doubler.

comparison of two options (SASE and frequency doubler) we performed two dedicated runs at FLASH2 operating with electron energies close to the limit. First, standard SASE mode has been optimally tuned at full undulator length, and radiation pulse energy scanned versus radiation wavelength. Then frequency doubler scheme has been tuned optimally with the same electron beam, and the pulse energy scanned. Results of pulse energy measurements are compiled in Fig. 5. We see that visibly shorter wavelengths were reached with the frequency doubler. In particular, photon energies above Nitrogen K-edge have been demonstrated which significantly exceeds original specifications of FLASH2. The radiation has been successfully transported to FLASH2 experimental hall.

Analysis of experimental results obtained at FLASH2 shows that the frequency doubler scheme works in good agreement with theoretical expectations. Its tuning does not require special efforts, and it starts to work when SASE process tuned along the whole length of the undulator. Two color mode of operation is rather robust for longer wavelengths. Minimum achievable wavelength, strongly depends on the quality of the electron beam which requires dedicated tuning of the beam formation system. However, this is general problem for SASE FEL as well. Presently we reached photon energies just below Nitrogen K-edge (400 eV), and this seems to be close to the limit of the doubling frequency technique at he energy of electron beam of 1230 MeV. Additional installation of two undulator sections (2 $\times$ 2.5 m) may help in more reliable covering of the Nitrogen K-edge range and reaching shorter wavelengths.

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