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TWO-COLOR OPERATION OF FLASH2 UNDULATOR

E.A. Schneidmiller*, M. Braune, B. Faatz, F. Jastrow, M. Kuhlmann,
A. Sorokin, K. Tiedtke, and M.V. Yurkov
DESY, Hamburg, Germany

Abstract

FLASH is the first soft X-ray FEL user facility, routinely providing brilliant photon beams for users since 2005. The second undulator branch of this facility, FLASH2, is gap-tunable which allows to test and use advanced lasing concepts. In particular, we tested recently a two-color mode of operation based on the alternation of tunes of the undulator segments (every other segment is tuned to the second wavelength). This scheme is advantageous in comparison with a subsequent generation of two colors in two consecutive sections of the undulator line. First, source positions of the two FEL beams are close to each other which makes it easier to handle them. Second, the amplification is more efficient in this configuration since the segments with respectively "wrong" wavelength still act as bunchers. We developed methods for online intensity measurements of the two colors simultaneously that require a combination of two detectors. We present some examples of such measurements in the XUV and soft X-ray regimes.

INTRODUCTION

Two-color lasing is a popular operation mode of X-ray FEL user facilities. A possible way to generate two colors in a gap-tunable undulator, operating in SASE regime, is to split the undulator into two sections, and set different K-values in each of these sections. An additional useful element for X-ray pump, X-ray probe experiments could be a chicane between the two sections to control a time delay between the pulses of two different colors. One can use the same electron bunch (parts of the same bunch) for lasing in the two sections of the undulator [1]. In this case the beam quality is partially spoiled in the first section (that typically operates at the onset of saturation), and one has to compromise intensities of two colors. As an alternative, one can use fresh-bunch technique based on the principle of the betatron switcher [2]. A practical realization of this principle was done in a way that the head and the tail of the bunch lase in two different sections of the undulator [3,4].

One of the issues with these sectioned-undulators schemes (or, split undulators) is a significant spatial separation of effective source positions of the two X-ray beams. This separation can make it difficult to efficiently focus both beams on a sample. As an alternative, one can consider two-color lasing in the undulator with the alternation of tunes of single undulator segments enabling close positions of source points. This scheme was realized at LCLS for small separation of tunes (about 1%) and was described in [5] as the gain-modulated FEL.

* evgeny.schneidmiller@desy.de

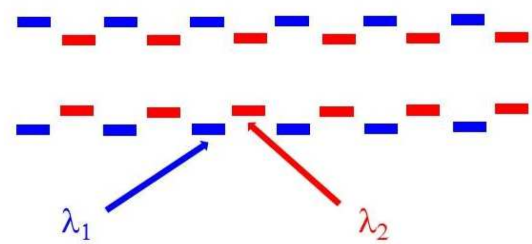

Figure 1: Conceptual scheme of two-color lasing with the alternation of undulator tunes.

We tested the two-color mode with the alternation of undulator tunes at FLASH [6,7] in the regime of a large separation of tunes (several tens percents), and present the main results in this paper.

TWO-COLOR LASING WITH THE ALTERNATION OF UNDULATOR TUNES

The principle of operation of the described two-color scheme is simple. Let us consider the gap-tunable undulator of the FLASH2 branch of the soft X-ray free electron laser facility FLASH [7]. The undulator consists of twelve 2.5 m long segments, maximum K-value is 2.7. For generation of two colors, all odd segments are tuned to wavelength λ_1, and even segments to λ_2 (see Fig. 1). With respect to the amplification of the electromagnetic wave with the wavelength λ_1, the FEL process is disrupted as soon as the electron beam leaves λ_1 segment and enters a "wrong" segment tuned to λ_2. However, energy modulations in the electron bunch, accumulated due to the interaction with the electromagnetic field in the λ_1 segment, continue to get converted into density modulations (bunching) in the λ_2 segment due to its longitudinal dispersion. Thus, in the next λ_1 segment the beam with an enhanced bunching quickly radiates a stronger field than the one coming from the previous λ_1 segment (which in addition is diffracted), and the FEL process continues with higher amplitudes. In some sense the mechanism is similar to that of the multi-stage (or distributed) optical klystron [8–11]. In this qualitative description we do not consider effects of longitudinal velocity spread due to the energy spread and emittance of the electron beam. According to our estimates, these effects were practically negligible in our experiments.

The longitudinal dispersion of an undulator segment is characterized by a transfer matrix element $R_{56} = 2N_w\lambda$, where N_w is the number of undulator periods per segment and λ is the resonance wavelength. If $\lambda_1 < \lambda_2$, the FEL gain is, obviously, weaker for λ_1 in the corresponding λ_1

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segments. However, the R_{56} in λ_2 segments is stronger and gives a larger addition to the final gain at λ_1 wavelength. Thus, the total gain in the linear regime can be comparable even if λ_1 is significantly shorter than λ_2. In principle, the number of segments does not have to be the same for λ_1 and λ_2, and we also tried 7 + 5 configuration. But typically 6 + 6 case was better in the sense of reaching comparable intensities.

If the undulator line is sufficiently long, nonlinear effects start to play a role in the last segments. In this case the amplification processes at both wavelengths are not independent anymore, and they start to compete in terms of modification of longitudinal phase space of the electron beam. As a result, the radiation power is somewhat smaller compared to standard single-color lasing in saturation regime. However, it can still be sufficient for many experiments.

SIMULTANEOUS MEASUREMENTS OF TWO COLORS

As it was mentioned, two colors are not generated independently, so that one can not measure their intensities by turning off one color and measuring the other one (and vice versa). Moreover, in case of user experiments one should have online nondisruptive measurements. Thus, one of the goals of our studies was to develop methods for such measurements. It is obvious that we can find pulse energies of each of the X-ray beams as soon as we have two linear detectors. In this case we have a system of two linear equations with two unknowns, and should be able to easily retrieve pulse energies at λ_1 and λ_2.

We have four of such detectors available in the FLASH2 tunnel and experimental hall: two gas monitor detectors (GMDs) for measurements of absolute pulse energy [12], the online photoionization spectrometer (OPIS) for non-invasive wavelength measurements [13], and micro-channel plate (MCP) detector for pulse energy measurements with a large dynamic range [14]. Note that in the following we refer to ensemble averaged pulse energies throughout the text.

As an example, let us consider the measurement we did with the tunnel GMD and OPIS. Note that both devices are placed in the tunnel next to each other, and there are no transmission effects that can be different for two X-ray beams. In the time-of-flight spectra of the OPIS, relative intensities of the two X-ray colors can be determined since the signals of the respective photoelectrons are separated in arrival time due to different kinetic energies. From these signal intensities a ratio of number of photons of the two wavelengths can be evaluated. Thus, we have the first linear equation:

$$N_2 = pN_1 \,, \tag{1}$$

where N_1 and N_2 are unknown average photon numbers, and p is the measured coefficient. If the tunnel GMD is set to the measurements of pulse energy at λ_1, it will show spurious pulse energy $\tilde{\mathcal{E}}_{gmd}$ when the second color is present:

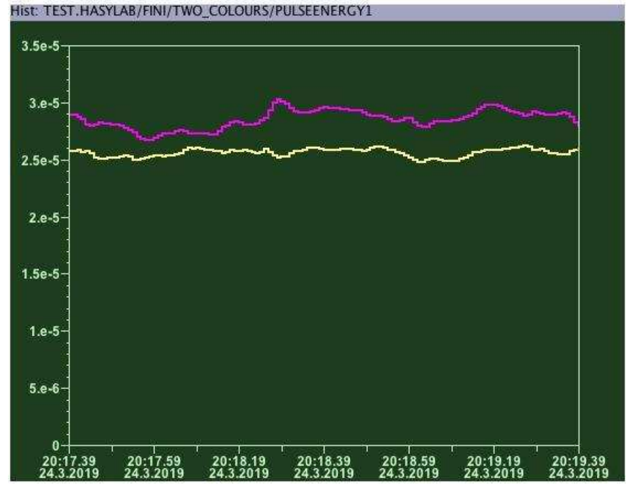

Figure 2: Online measurement of FEL intensities in two-color mode with two gas monitor detectors. Pulse energies in Joules are shown for 7 nm (yellow) and for 10 nm (pink) versus real time.

$$\tilde{\mathcal{E}}_{gmd} = \hbar\omega_1 \left(N_1 + N_2 \frac{\sigma_2\gamma_2}{\sigma_1\gamma_1} \right) . \tag{2}$$

Here $\sigma_{1,2}$ are the photoionization cross sections and $\gamma_{1,2}$ are the mean charges for a given gas and the two photon energies (see, e.g. [15]), $\omega_1 = 2\pi c/\lambda_1$. Solving Eqs. (1) and (2) for N_1 and N_2, we get the final result for the actual pulse energies $\mathcal{E}_1 = \hbar\omega_1 N_1$ and $\mathcal{E}_2 = \hbar\omega_2 N_2$:

$$\mathcal{E}_1 = \frac{\tilde{\mathcal{E}}_{gmd}}{1 + p\frac{\sigma_2\gamma_2}{\sigma_1\gamma_1}} \quad , \quad \mathcal{E}_2 = p\mathcal{E}_1 \frac{\omega_2}{\omega_1} \,. \tag{3}$$

In a similar way one can get simple expressions for the combination of the MCP-based detector and the tunnel GMD. The MCP detector can be cross-calibrated with the GMD at a certain wavelength, say λ_1. When two X-ray beams are present, it shows a linear combination of two actual pulse energies: $\tilde{\mathcal{E}}_{mcp} = \mathcal{E}_1 + s\mathcal{E}_2$. It is interesting to note that in the wavelength range of our experiments we had $s \simeq 1$. Combining this equation with Eq. (2), we obtain the actual pulse energies.

Finally, we did the measurements with two GMDs, one in the tunnel and one in the experimental hall. They have to be filled with different gases, then Eq. (2) can be also used for the second GMD but with the different constants σ and γ. Moreover, we should correct the photon numbers N_1 and N_2 in that equation for the beamline transmission that has to be measured once for each wavelength individually. Then we have again the system of two equations from which we obtain actual pulse energies. The two-color measurement with two GMDs is now integrated into GMD server and can be used online for tuning and monitoring of this operation mode at FLASH2 (see Fig. 2).

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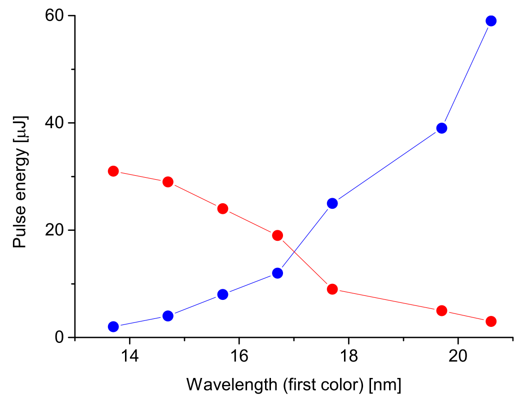

Figure 3: Pulse energies of two XUV beams measured with the GMD+OPIS method. The first color (odd undulator segments) is scanned between 13.7 nm and 20.6 nm (shown in blue). The second color (even segments) stays tuned at 22.6 nm (shown in red).

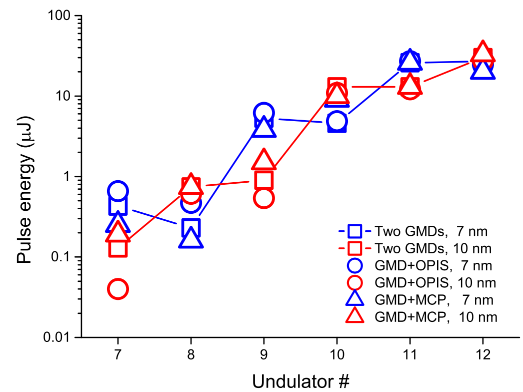

Figure 4: Gain curve of two-color lasing. Pulse energies at 7 nm (blue) and at 10 nm (red) versus the undulator segment number. Measurements were done with three methods: two GMDs (squares), GMD+OPIS (circles), and GMD+MCP (triangles).

SOME EXPERIMENTAL RESULTS

In this Section we present some results related to the two-color operation in the FLASH2 undulator branch. On January 23, 2019 we demonstrated two-color lasing in XUV regime. Accelerator energy was 760 MeV, bunch charge was 0.3 nC. Wavelengths were measured with the OPIS and with a wide-spectral-range XUV spectrometer [16], both spectrometers showed the same results within 0.1 nm. Pulse energies were measured with the help of OPIS and the tunnel GMD as described in the previous Section. We explored the wavelength range from 13 nm to 27 nm, pulse energies were between a few microjoules and several tens microjoules. We also studied a possibility of scanning one wavelength while the other stayed constant, and present here an example of such a scan (see Fig. 3). The undulator was in 6 + 6 configuration: the even segments were kept tuned to λ_2 = 22.6 nm, while the odd segments were scanned in the range of λ_1 between 13.7 nm and 20.6 nm. One can see from Fig. 3 that wavelength scan in a wide range is possible but the two colors are not generated independently. When we increase λ_1, pulse energy at this wavelength increases significantly at the expense of the pulse energy reduction at a fixed λ_2.

On March 24, 2019 we could run FLASH accelerator at 1235 MeV (close to the maximum energy) with a bunch charge of 0.3 nC. We were able to operate in soft X-ray regime and to find the shortest wavelengths at which we could operate FLASH2 undulator in two-color mode with reasonable intensities of both X-ray beams. We used a significant frequency separation, and could get, for example, about 30 µJ at 7 nm and at 10 nm wavelengths simultaneously (see Fig. 2). We could reduce wavelengths to 6 nm and 9 nm with pulse energies being at the level of a few microjoules. For simultaneous lasing at 7 nm and 10 nm we could measure a part of the FEL gain curve (see Fig. 4) using three methods described in the previous Section. In general, the three methods showed a reasonable agreement at high intensity level, when the FEL operated in nonlinear regime and the intensities were relatively stable.

In conclusion, we were able to successfully demonstrate two-color lasing with the alternation of undulator tunes at FLASH. The methods for simultaneous measurement of two colors were developed, operational limits in terms of wavelengths and pulse energies were determined. Two-color mode can be offered to users of FLASH2.

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