FLASH Reaching the Transition Metals

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Abstract

There is a general interest in reaching shorter wavelengths in Free-Electron Lasers. There are several ways of achieving this. This report deals with reaching the so-called transition metals down to 1.3 nm with an afterburner undulator with variable polarization at a relatively low electron beam energy. It will be shown that with an increase of about 200 MeV and moderate changes, this can be achieved in the present FLASH facility.

1 Introduction

FLASH has been successfully delivering SASE radiation to users for over 7 years [1, 2]. Every few years, the machine has been upgraded in energy to reach shorter wavelengths. The present energy of 1.25 GeV exceeds its original specifications and the minimum wavelength which has been reached is now 4.2 nm (delivered to users).

FLASH has fixed gap undulators, which means that each wavelength change needs a change in energy. The present FLASH upgrade, called FLASH II, foresees a variable gap undulator in a separate beamline [3]. The undulator parameters have been chosen such, that for any given electron beam energy, which determines the wavelength in the fixed-gap undulators, the wavelength in the new undulator line can still be tuned by a factor of 4.

An obvious next step after the present upgrade is to exchange the fixed gap undulator with a variable gap device and simultaneously an additional energy upgrade. An important question is what the optimal parameters for the new insertion device would be, which is related to the wavelength which one wants to achieve. Both beam energy and undulator parameters need to be optimized at the same time.

The wavelength ranges that are interesting from an experimental point of view are:

- The water window reaching from approximately 2.3 to 4.3 nm.
- The transmission metals used for magnetism in the wavelength range between 1.3 and 1.6 nm.

The study presented here investigates the different possibilities to reach these transition metals. Possible options are

- An energy upgrade and an exchange of the undulator to reach 1.3 nm directly, either with a fixed gap undulator or with some tunability.
- An energy upgrade and an exchange of the undulator to reach 1.5 nm directly, again with either a fixed gap undulator or with some tunability.
- An energy upgrade to reach either wavelengths in a 2^{nd} harmonic afterburner. The main undulator would have a tuning range whereas the afterburner is fixed gap.

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- Only an energy upgrade to reach either wavelengths in a 2$^{\text{nd}}$ harmonic afterburner. The main undulator is the present one, e.g. 27.3 mm and only an afterburner would need to be built.
- Same as the previous scheme, but now in FLASH2. The advantage would be that the entire geometry both in the tunnel and the photon transport is optimized to include the shorter wavelengths.

An alternative approach, changing the undulator but keeping the energy at 1.25 GeV, has been described in Ref. [4].

2 Basic FEL and Undulator Formulas

In this section some well known equations, which are needed for our further studies, are presented. One can find detailed derivations of these formulas in [5] and [6].

The radiation wavelength of the Free-Electron Laser is defined by the undulator period λ_{u}, undulator strength K, as well as by the electron beam energy (or relativistic factor γ). The relationship is given by the so-called FEL resonance condition:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2\right), \tag{1}$$

where $K = e\lambda_u H/2\pi m_e c$, with $-e$ and m_e are the charge and the mass of the electron, c is the speed of light in vacuum and H is the magnetic field on the axis of the undulator. For a planar undulator, K and H are RMS values, for a helical undulator, they represent peak values. The on-axis peak field of the undulator can be approximated by [7]

$$H = Ae^{B\frac{g}{\lambda_{\mathrm{u}}} + C(\frac{g}{\lambda_{\mathrm{u}}})^2}, \tag{2}$$

where g is the undulator gap and the coefficients A, B and C are defined by the structure of the undulator. Substituting Eq. (2) into the expression of K, one can rewrite that expression as follows:

$$K = \frac{e\lambda_u}{2\pi m_e c} Ae^{B\frac{g}{\lambda_u} + C(\frac{g}{\lambda_u})^2}. \tag{3}$$

3 The minimum Energy needed to reach shorter wavelengths

We performed our studies for four wavelengths, namely 1.3, 1.5, 2.6 and 3.0 nm, where the latter two are of interest if 1.3 and 1.5 nm can only be reached in an afterburner scheme at the second harmonic (see Sec. 4). From Eqs. (1) and (3) it can be seen that the shortest possible wavelength is reached for the small undulator period at the smallest possible undulator gap. Although there is no hard limit on either number, some guidelines can be followed. For the transition metals, one usually is interested in radiation of variable polarization. Since these undulators so far have not been built as in-vacuum devices, we will assume a minimum undulator gap of 9 mm, leaving an inner diameter for the vacuum pipe of around 7.5 mm, which for FLASH parameters has been shown to be close to the minimum which can be handled with acceptable beam losses. In order to get enough radiation power into the FEL beam, a minimum K-value of 1 is normally assumed for planar undulators, resulting on an RMS value of $1/\sqrt{2}$ or approximately 0.7. These values for undulator gap and minimum K will be used throughout this paper.

The undulator period for which these values can be achieved depends on the undulator technology used. The studies are performed for several types of undulators:

- Hybrid with Vanandium Permendur planar undulators (A = 3.694, B = -5.068, C = 1.520)

- Pure Permanent Magnet Helical Field (APPLE II) helical undulators (A = 1.614, B = -4.67, C = 0.620)
- APPLE III (A = 1.4 × 1.614, B = -4.67, C = 0.620)
- DELTA (A = 1.7 × 1.614, B = -4.67, C = 0.620)

For the planar and APPLE II undulator, he coefficients are based on simulations of structures with differnt periods and gaps, which have been summarized in Ref. [7]. For the APPLE III and DELTA type undulator, it is only an estimate for a limited set of parameters [8].

The minimum energy needed to reach the four wavelengths mentioned earlier is reached for an undulator gap of 9 mm and a K of 0.7. Solving the Eq. (3) with respect to λ_{u}, one can find the corresponding undulator periods for different types of undulators. For all of these undulator periods the required energies to achieve the desired wavelengths are given in Table 1.

Table 1: Energy values for different undulator types needed to reach wavelengths of 1.3, 1.5, 2.6 and 3.0 nm. The undulator periods in column 2 are chosen such that for a gap of 9 mm, the K of the undulator is 0.7, where in case of the planar undulator, this is the RMS-value of the field.

Type	Period (mm)	1.3 nm (GeV)	1.5 nm (GeV)	2.6 nm (GeV)	3.0 nm (GeV)
Planar	20.3	1.75	1.63	1.24	1.15
APPLE II	24.3	1.91	1.78	1.35	1.26
APPLE III	21.4	1.80	1.67	1.27	1.18
DELTA	19.9	1.73	1.61	1.23	1.14

As already mentioned in the introduction, the maximal achieved energy at FLASH is 1.25 GeV and so one needs significant energy upgrade to achieve 1.3 and 1.5 nm wavelengths.

3.1 The energy needed to reach shorter wavelengths with Undulator Tunability

The energies calculated in the previous section are minimum energies, needed when the undulator has its minimum gap of 9 mm and its minimum period, where the K-value of 0.7 can be reached. This, however, would be a significant restriction on operation of both undulator lines simultaneously. Therefore, it is preferred to be able to tune the wavelength by varying the undulator gap as well. As will be shown here, the consequence of the additional wish of having gap tunability will increase the undulator period and, consequently, increase the energy at which the desired wavelengths can be reached. To achieve factor of 2 tunability in wavelength, we need to change the undulator gap such that the new undulator strength K_2 satisfies the condition below (obtained from Eq. (1)):

$$\frac{\lambda_1}{\lambda_2} = \frac{1+K_1^2}{1+K_2^2} = 2. \tag{4}$$

With again as boundary condition that the minimum $K = K_2 = 1/\sqrt{2}$, from Eq. (4) it follows that the maximum value is $K_2 = \sqrt{2}$, which needs to be reached for the minimum gap of 9 mm. With $K_1 = \sqrt{2}$ at $g_1 = 9\,\mathrm{mm}$, the undulator period is fixed for each of the undulator technologies chosen in accordance with Eq. (3). For the lower value of K one is able to obtain from Eq. (3) the undulator gap g_2:

$$B\frac{g_2}{\lambda_u} + C\left(\frac{g_2}{\lambda_u}\right)^2 = B\frac{g_1}{\lambda_u} + C\left(\frac{g_1}{\lambda_u}\right)^2 - \ln 2. \tag{5}$$

One of the roots of Eq. (5) is unphysical. In Table 2, the remaining solutions are shown in column 3. The additional columns show the required energies to achieve the wavelengths for the gaps for which the undulator strength is 0.7 at the respective undulator periods.

Table 2: Energies needed to reach the desired wavelengths of 1.3, 1.5, 2.6 and 3.0 nm with an undulator tunability of a factor of two for an undulator period given in column 2 and a gap given in column 3. The minimum gap is assumed to be 9 mm.

Type	Period (mm)	Gap (mm)	1.3 nm (GeV)	1.5 nm (GeV)	2.6 nm (GeV)	3.0 nm (GeV)
Planar	26.8	13.9	2.02	1.88	1.42	1.32
APPLE II	32.6	14.3	2.23	2.07	1.58	1.46
APPLE III	28.0	13.7	2.05	1.91	1.45	1.34
DELTA	25.9	13.3	1.98	1.85	1.48	1.3

Table 3: Parameters used for Simulations. The undulator parameters are those used for the simulations in Sec. 4.3.

Electron beam		FLASH1	FLASH2
Peak current	kA	2.5	2.5
Emittance, norm. (x,y)	mm mrad	1.4	1.4
Bunch charge	nC	0.06 & 0.2	0.06 & 0.2
Energy spread	MeV	0.2	0.5
Average β-function	m	6	6
Undulator		FLASH1	FLASH2
Period	mm	27.3	31.4
K-value		0.9	0.76
Segment length	m	4.5	2.5
Number of segements		8	12

As can be seen, the two longer wavelengths require only a moderate increase in energy, whereas the shorter wavelengths can only be reached when the energy is roughly doubled. Therefore, the idea of an afterburner is pursued in the next section.

4 Using an Afterburner Scheme to achieve shorter wavelengths

Another approach to reach the above mentioned wavelengths is to use a long undulator (we will refer to it as main undulator) tuned to 2.6 or 3.0 nm, then use the modulated electron beam from this undulator in a shorter undulator, the so-called afterburner, tuned to 1.3 or 1.5 nm, respectively. The second harmonic micro bunches will radiate coherently the fundamental frequency of the afterburner. Based on the energy values obtained earlier needed to reach 2.6 or 3.0 nm, we consider electron beam with energy of 1.4 GeV and an APPLE III undulator as afterburner.

In the following sections, all simulations are performed with the simulation code Genesis 1.3. Genesis 1.3 is a time dependent, 3-dimensional simulation code for FEL studies which solves self consistent equations of electron dynamics and FEL radiation [9]. The following beam parameters have been chosen for the simulations, where the undulator parameters in Table 3 are those for the existing FLASH1 and FLASH2 undulators, as simulated in Sec. 4.3.

4.1 Generation of 3.0 and 1.5 nm at 1.4 GeV beam Energy

In the Fig. 1 the dependence of K and g on λ_{u} (Eqs. (1) and (3)) are shown, needed to reach 3.0 nm at 1.4 GeV beam Energy.

For the afterburner, the K value and undulator period are calculated in case of radiation

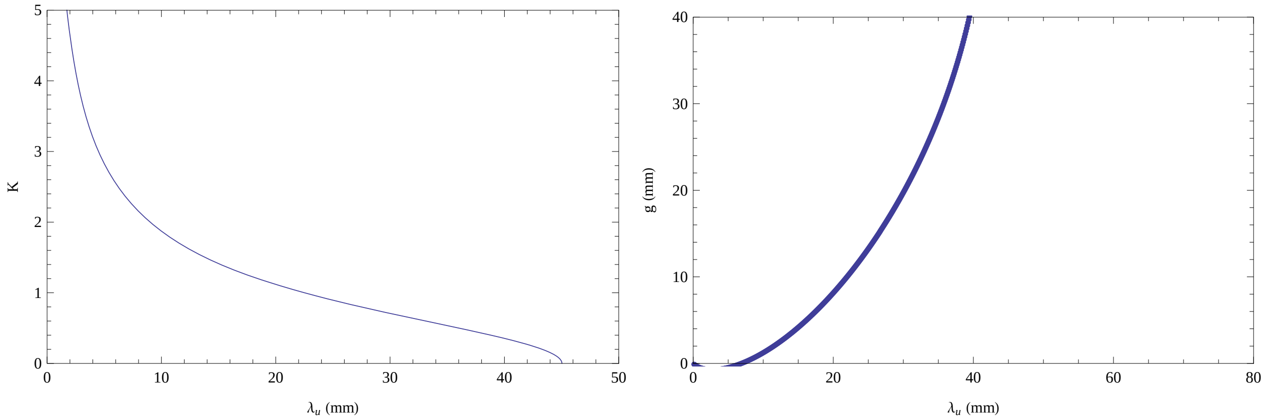

Figure 1: Undulator strength K (left) and gap g (right) versus λ_u needed to reach 3.0 nm at a beam energy of 1.4 GeV in a planar undulator.

wavelength of 1.5 nm, beam energy of 1.4 GeV (the same as in main undulator) and undulator gap of 9.5 mm (for APPLE III undulator): $K = 0.4417$ and $\lambda_\mathrm{u} = 18.8$ mm. Here the g-value of 9.5 mm instead of 9 mm is considered for safety reason. In case the magnetic field of the afterburner is smaller than estimated based on theoretical approximations, the gap can be closed slightly to compensate.

For the main undulator we consider two possibilities. First of them is to take the K value to be 0.7. For this case one can see from Fig. 1 that $\lambda_\mathrm{u} = 30.0$ mm. In Fig. 2 the power growth along the undulator for this case is presented. For the time-dependent simulations, two different electron beam charges have been taken, corresponding to an RMS bunch length of 10 and 30 fs. On the left, the power growth along the main undulator is shown, on the right, the power growth for the 2^{nd} harmonic. The power growth for the 3^{rd} harmonic is shown for reference only, since it is too small to be used in most practical applications.

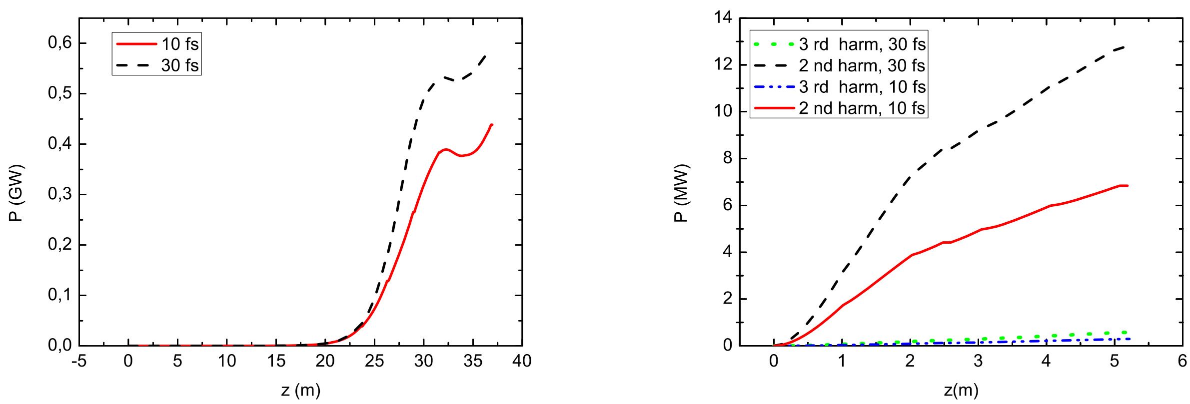

Figure 2: Power growth along the main undulator (left) and along the afterburner (right). Beam energy is 1.4 GeV, $K^{(main)} = 0.7$, $\lambda_u^{(main)} = 30.0$ mm. $K^{(afterburner)} = 0.4417$, $\lambda_u^{(afterburner)} = 18.8$ mm. Curves for the 3^{rd} harmonic are shown for reference.

The second possibility assumes a gap of 9 mm. From the Fig. 1 we can conclude that in this case the undulator period is $\lambda_\mathrm{u} = 21$ mm and the corresponding K-value is 1.075. In Fig. 3 the power growth along the undulator for this case is shown. The main difference with the previous case is that saturation in the main undulator is reach much earlier. The power level of the 2^{nd} harmonic is only slightly different for the 30 fs bunch length. The difference for the 10 fs case is larger, but there is no clear reason to explain this.

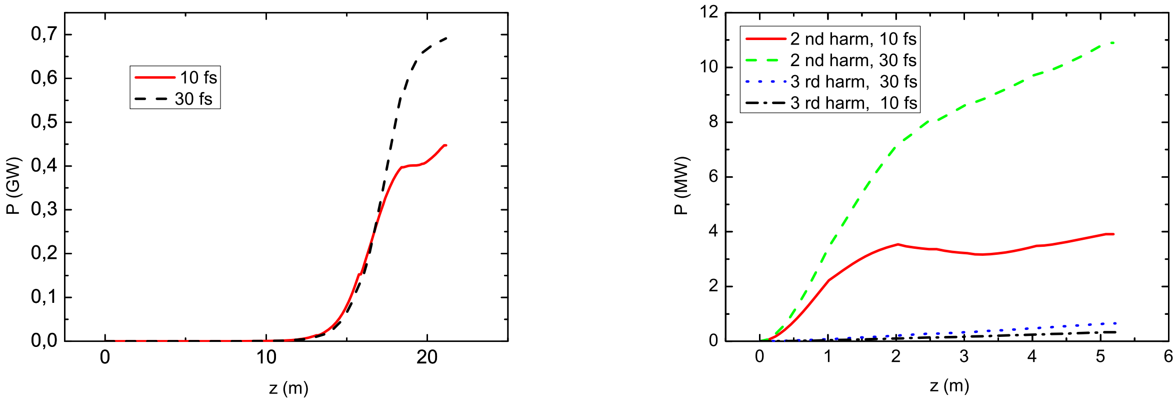

Figure 3: Power growth along the main undulator (left) and along the afterburner (right). Beam energy is 1.4 GeV, $K^{(main)} = 1.075$, $\lambda_u^{(main)} = 21.0$ mm. $K^{(afterburner)} = 0.4417$, $\lambda_u^{(afterburner)} = 18.8$ mm. Curves for the 3^{rd} harmonic are shown for reference.

4.2 Generation of 2.6 and 1.3 nm at 1.4 GeV beam Energy

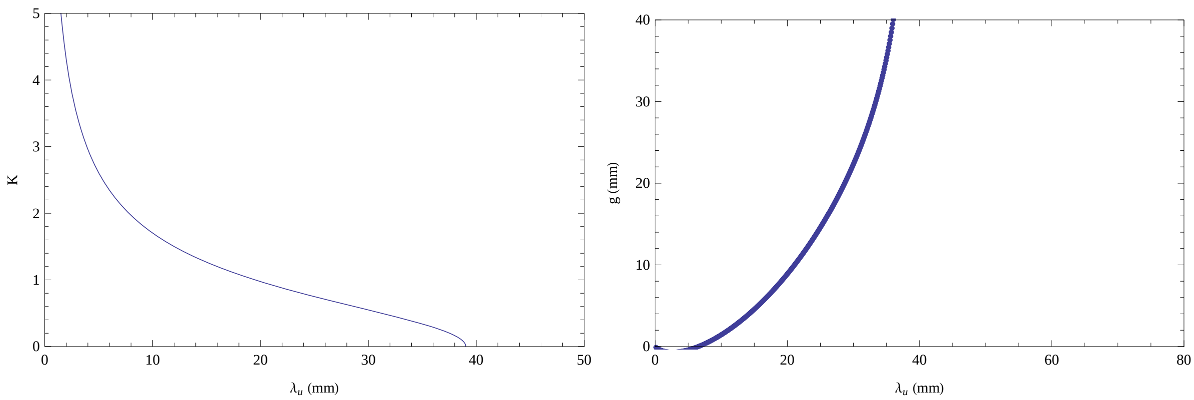

Figure 4: Undulator strength K (left) and gap g (right) versus λ_u needed to reach 2.6 nm at a beam energy of 1.4 GeV in a planar undulator.

A similar set of simulations is performed with optimized settings for 2.6 nm and its 2^{nd} harmonic of 1.3 nm. In the Fig. 4, the dependence of K and g on λ_u (Eqs. (1) and (3)) are shown. The K-value and undulator period are calculated in case of radiation wavelength of 1.3 nm, bunch energy of 1.4 GeV and undulator gap of 9.5 mm (for APPLE III Undulator): $K = 0.3464$ and $\lambda_u = 17.4$ mm. For the main undulator we again consider the two possibilities discussed in the previous section. First of them is to take the K value to be 0.7. For this case one can see from the Fig. 4 that $\lambda_\mathrm{u} = 26.0$ mm. In the Fig. 5 the power growth for this case is presented at 2.6 nm (left) and its 2^{nd} harmonic (right).

The second possibility assumes a gap of 9 mm. From Fig. 4 we can conclude that in this case the undulator period should be $\lambda_\mathrm{u} = 20$ mm and a corresponding K-value is 0.9709. In Fig. 6 the output power for this case is presented. As in the case of 3.0 and 1.5 nm, the main difference is that saturation is reached earlier at the higher K-value for the undulator. For the afterburner, there is virtually no difference.

4.3 Reaching 1.5 nm with the present Undulator

From the parameters used in the previous sections one can see, that the undulator period and gap are not too far away from the values that we have at the moment, assuming we

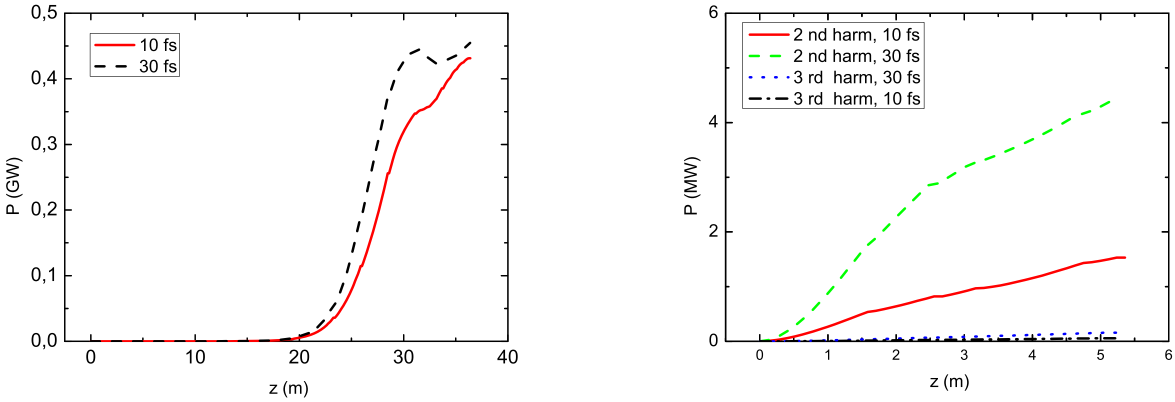

Figure 5: Power growth along the main undulator (left) and along the afterburner (right). Beam energy is 1.4 GeV, $K^{(main)} = 0.7$, $\lambda_u^{(main)} = 26.0$ mm. $K^{(afterburner)} = 0.47$, $\lambda_u^{(afterburner)} = 17.4$ mm. Curves for the 3^{rd} harmonic are shown for reference.

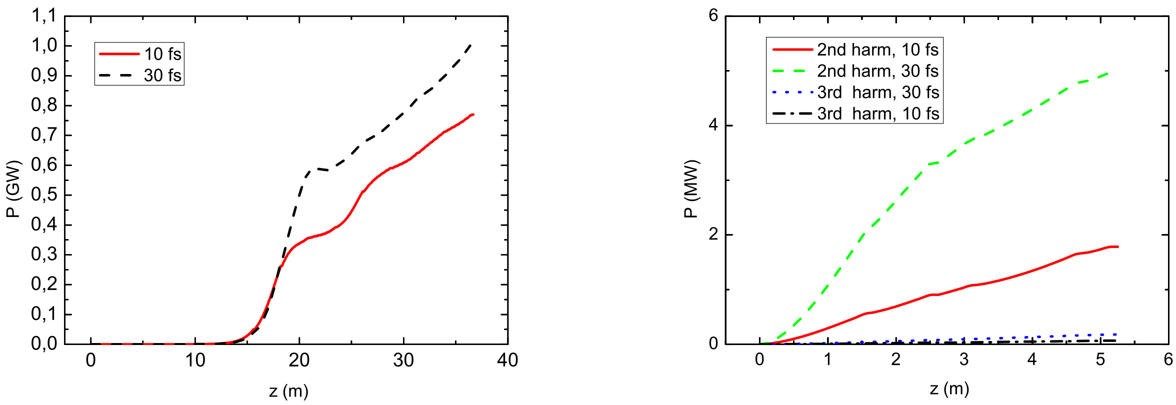

Figure 6: Power growth along the main undulator (left) and along the afterburner (right). Beam energy is 1.4 GeV, $K^{(main)} = 0.9709$, $\lambda_u^{(main)} = 20.0$ mm. $K^{(afterburner)} = 0.47$, $\lambda_u^{(afterburner)} = 17.4$ mm. Curves for the 3^{rd} harmonic are shown for reference.

limit ourselves to either 3.0 or 2.6 nm. Therefore, we consider an afterburner put behind the present FLASH undulator, either in FLASH1 (fixed gap and a period of 27.3 mm) or FLASH2 (variable gap and a period of 31.4 mm). The undulator strength at FLASH1 is 0.9. As it is easy to calculate from Eq. (1) the required beam energy to reach 3.0 nm with this undulator is 1.467 GeV. Assuming for the afterburner the gap to be 9.5 mm, one can calculate from Eqs. (1) and (3) (for APPLE III Undulator) that the required strength and undulator period to achieve 1.5 nm wavelength are $K = 0.505$ and $\lambda_u = 19.7$ mm. The same kind of calculation, but now for reaching 2.6 nm radiation, leads to the beam energy of 1.575 GeV. Since the wavelength change is obtained due to an energy change, the afterburner parameters should stay the same as they were before the energy change. Fig. 7 shows results of runs with FLASH1 parameters.

For comparison, we consider an afterburner put behind FLASH2 currently under construction. The undulator period of FLASH2 is 31.4 mm. For comparison with FLASH1 we want to take the same bunch energy of 1.467 Gev. As it is easy to calculate from the Eq. (1) the required undulator strength to achieve 3.0 nm radiation with this undulator is 0.757. Since we assume the same energy as for the simulation performed for the FLASH1 undulator, the afterburner parameters are the same as given in Fig. 7. Results for FLASH2

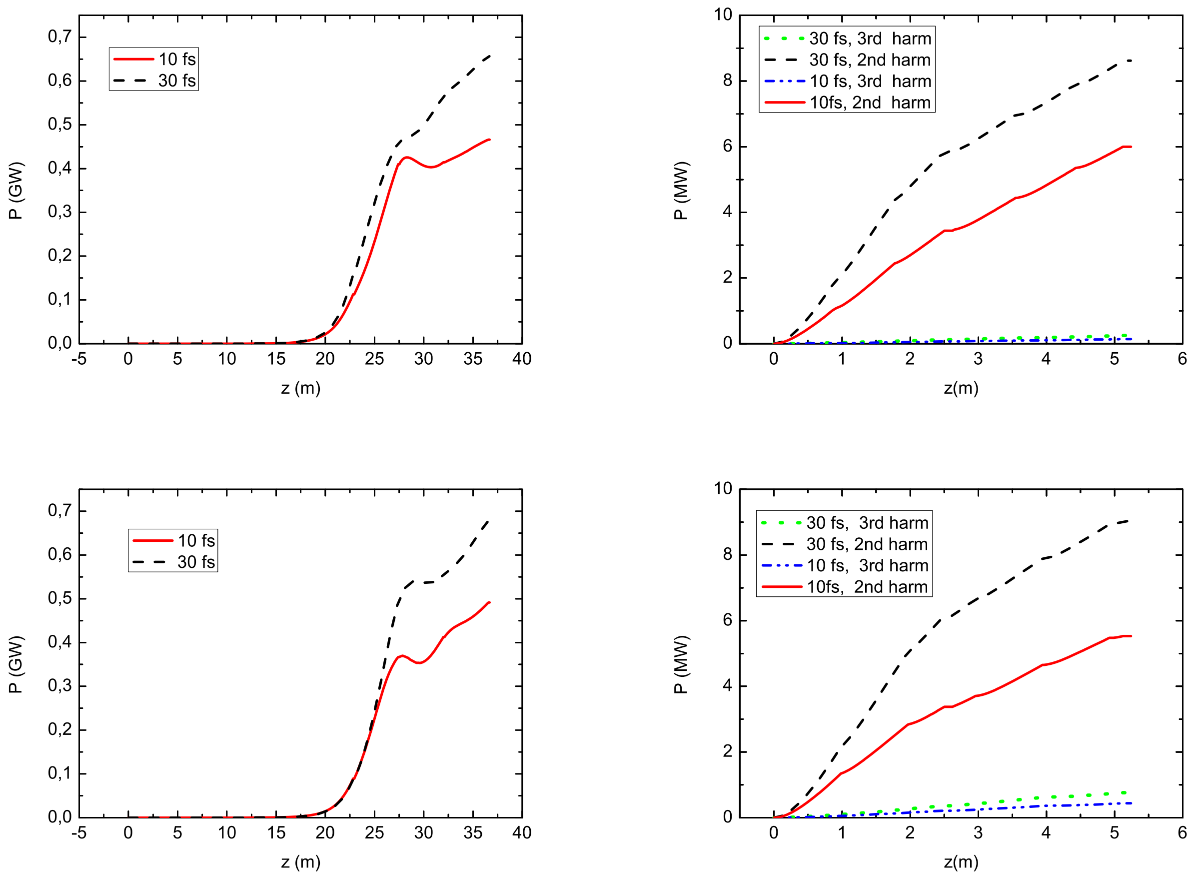

Figure 7: Power growth along the main undulator (left) and along the afterburner (right). The figures at the top show the results at a beam energy of 1.467 GeV, corresponding to 3.0 nm in the main undulator. The two figures at the bottom show the result at a beam energy of 1.575 GeV, corresponding to a wavelength of 2.6 nm in the main undulator. $K^{(main)} = 0.9$, $\lambda_u^{(main)} = 27.3$ mm, $K^{(afterburner)} = 0.505$, $\lambda_u^{(afterburner)} = 19.7$ mm. Curves for the 3^{rd} harmonic are shown for reference.

are shown in Fig. 8.

Note that even though clearly for FLASH2, saturation is not reached in the main undulator, the power at the 2^{nd} harmonic in the afterburner is similar to the result shown for FLASH1. What cannot be shown in these simulations, however, is that the power fluctuation will probably increase because of power fluctuation in the main undulator (both due to intrinsic SASE fluctuation and due to machine instabilities). An advantage of using FLASH2 would clearly be if more energy would be available, one could slightly change (decrease) the undulator gap to obtain the same wavelength. An excess in energy for FLASH1 would not be an advantage, since the undulator parameters are completely fixed.

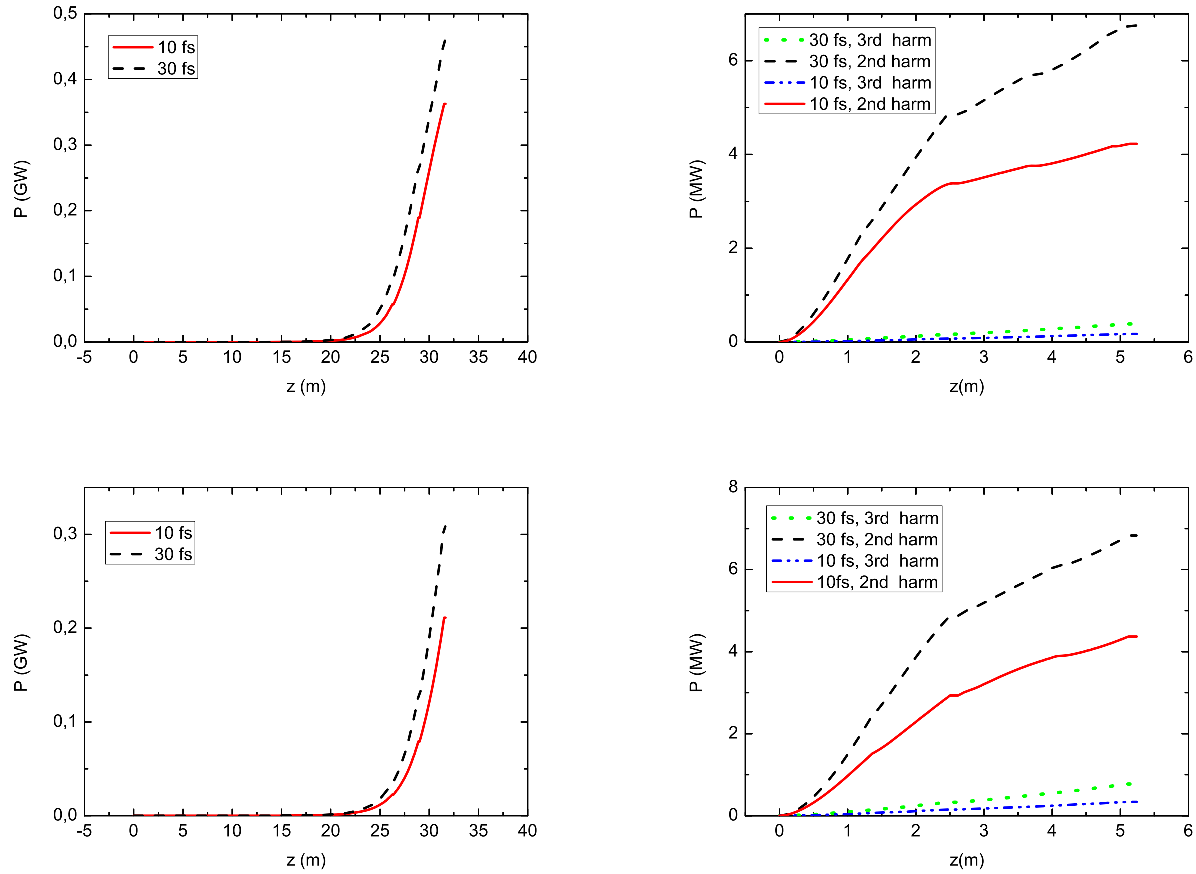

Figure 8: Power growth along the main undulator (left) and along the afterburner (right). The figures at the top show the results at a beam energy of 1.467 GeV, corresponding to 3.0 nm in the main undulator. The two figures at the bottom show the result at a beam energy of 1.575 GeV, corresponding to a wavelength of 2.6 nm in the main undulator. $K^{(main)} = 0.758$, $\lambda_u^{(main)} = 31.4$ mm, $K^{(afterburner)} = 0.505$, $\lambda_u^{(afterburner)} = 19.7$ mm. Curves for the 3^{rd} harmonic are shown for reference.

5 Summary of the Simulation Results

It should be noted that simulations have been performed for 3.0 and 1.5 nm, whereas the actual wavelength of interest are 3.18 and 1.59 nm. The 20 MeV addtional energy needed is considered a safety margin. Also, the total undulator length assumed for FLASH1 consists of 8 segments of 4.5 m instead of 6 that are presently installed in the tunnel. There are, however, 3 additional undulators available that were taken out during the upgrade in 2003. However, the additional space required would result in significant changes of the vacuum line upstream. Limiting the undulator length to the present 6 segments would result in a similar situation that has been shown for FLASH2, where saturation was not reach, probably resulting in large fluctuation in intensity at the harmonic.

The simulation results are presented in Tables 4 and 5 for two different electron bunch lengths (10 fs and 30 fs) and for two positions in the afterburner (in the middle and in the end). They show that with an energy upgrade of about 200 MeV, only a short afterburner is needed to obtain pulses of variable polarization, a pulse length shorter than 100 fs with a pulse energy exceeding 1 μJ.

Table 4: Results of time dependent genesis 1.3 simulations for 1.4 GeV electron bunch.

Simulation Parameters	Pulse Energy(μ J)	Power (MW)	Pulse Length (fs)	Pulse Energy (μ J)	Power (MW)	Pulse Length (fs)
2.6 nm 9 mm gap						
2^{nd} harm 10fs	0.1068	2.423	44.09	0.2101	4.612	45.56
2^{nd} harm 30fs	0.7799	8.674	89.91	1.184	13.61	86.98
2.6 nm K=0.7						
2^{nd} harm 10fs	0.09809	2.687	36.51	0.1823	5.86	31.11
2^{nd} harm 30fs	0.6876	7.617	90.27	1.043	11.72	88.99
3.0 nm 9 mm gap						
2^{nd} harm 10fs	0.3404	9.086	37.46	0.3929	9.5	41.36
2^{nd} harm 30fs	1.778	23.12	76.91	2.406	33.68	71.45
3.0 nm K=0.7						
2^{nd} harm 10fs	0.4135	12.17	33.99	0.6872	19.24	35.71
2^{nd} harm 30fs	1.86	18.73	99.34	2.813	29.99	93.82

Table 5: Results of time dependent genesis 1.3 simulations for existing undulators. The simulations for 3.0 nm have been performed at an electron beam energy of 1.467 GeV, for 2.6 nm the energy was 1.575 GeV.

Simulation Parameters	Pulse Energy(μ J)	Power (MW)	Pulse Length (fs)	Pulse Energy (μ J)	Power (MW)	Pulse Length (fs)
FLASH1 2.6 nm						
2^{nd} harm 10 fs	0.2906	6.827	42.57	0.5119	12.02	42.59
2^{nd} harm 30 fs	1.309	12.41	105.5	1.921	16.83	114.1
FLASH1 3.0 nm						
2^{nd} harm 10fs	0.2921	6.891	42.39	0.5623	13.14	42.79
2^{nd} harm 30fs	1.253	11.01	113.8	1.846	15.42	119.7
FLASH2 2.6 nm						
2^{nd} harm 10fs	0.2733	8.698	31.42	0.4581	13.79	33.22
2^{nd} harm 30fs	1.065	11.41	93.28	1.537	17.02	90.27
FLASH2 3.0 nm						
2^{nd} harm 10fs	0.3321	9.556	34.75	0.4501	11.88	37.9
2^{nd} harm 30fs	1.023	11.19	91.43	1.531	16.23	94.34

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