FLASH Reaching the Transition Metals

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1 Introduction

FLASH has been successfully delivering SASE radiation to users for over 7 years. 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).

One of the disadvantages of the design is that FLASH has fixed gap undulators. This means that each wavelength change needs a change in energy and therefore of the optics along a significant part of the machine. The next step is therefore to implement in a new undulator line with variable gap undulators. This enables a tunability of two undulators over a large wavelength range. In order to achieve this, the undulator period for FLASH II had to be chosen rather large.

Because the electron beam quality is better than was expected in the original design, we can go to shorter wavelengths. However, this is obviously only possible for shorter undulator periods. Therefore, an upgrade of FLASH I (the present undulator line) aims at shorter wavelengths.

There are several wavelength ranges that are interesting from an experimental point of view.

- The waterwindow reaching from approximately 2.3 to 4.3 nm. This wavelength range allows for in-vitro experiments in Biology.
- The transmission metals used for magnetism in the wavelength range between 1.3 and 1.6 nm. They are of specific interest for magnetic media, such as hard discs.

This study 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 2nd harmonic afterburner. The main undulator would have a tuning range whereas the afterburner is fixed gap.
- Only an energy upgrade to reach either wavelengths in a 2nd 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 FLASH 2. The advantage would be that the entire geometry both in the tunnel and the photon transport is optimized to include the shorter wavelengths.

2 Basic FEL and Undulator Formulas

In this section some well known FEL formulas, which are needed for our further studies, are presented. One can find detailed derivations of these formulas in [1] and [2].

The radiation frequency of the Free-Electron Laser is defined by the undulator parameters (undulator period λ_u and undulator strength K), as well as by the electron bunch energy (or relativistic gamma factor γ). The relationship is presented in Eq. (1) (so called FEL resonance formula).

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K_{\mathrm{rms}}^2), \tag{1}$$

where $K_{\rm rms}$ is the RMS value of the undulator strength, the peak value of undulator strength is defined by $K_{\rm peak} = \frac{e\lambda_u}{2\pi m_e C} B_{\rm peak}$, m_e is the mass of the electron, C is the speed of light in vacuum and $B_{\rm peak}$ is the peak magnetic field on the axis of the undulator.

From the previous studies it is well known that the peak field created by the undulator magnets on the undulator axis can be approximated by Eq. (2) [3].

$$B_{\rm peak} = a e^{b \frac{g}{\lambda_{\rm u}} + c (\frac{g}{\lambda_{\rm u}})^2}, \tag{2}$$

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 the $K_{\rm peak}$ one can rewrite that expression as follows:

$$K_{\rm peak} = \frac{e\lambda_u}{2\pi m_e C} a e^{b \frac{g}{\lambda_u} + c (\frac{g}{\lambda_u})^2}. \tag{3}$$

3 On the Idea of Energy Upgrade

We performed our studies for four wavelengths, namely 1.3, 1.5, 2.6 and 3.0 nm. As it is easy to note the smaller the undulator gap the bigger the magnetic field on the undulator axis which on the other hand leads to bigger undulator strength. The bigger the latter the more radiation power one will have in the output. However, the gap can not be made arbitrarily small because of obvious technical reason: the minimal diameter for the vacuum pipe through what the bunch is travelling can not be made smaller than 9 mm, otherwise we will deal with electron loses. Taking into account the latter we aimed to understand which energies are needed to obtain mentioned above four wavelengths in case of the fixed-gap undulator with $g = 9mm$ with a undulator strength of $K_{\rm rms} = 0.7, (K_{\rm rms} = K_{\rm peak}/\sqrt{2} = 1/\sqrt{2} \approx 0.7)$. The studies are performed for several types of undulators [3]:

- 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)

Solving the Eq (3) numerically with respect to $\lambda_{\rm u}$ one can find the undulator periods for different types of undulators (see Table 1).

Table 1: Undulator periods for which $K_{\rm peak} = 1$ at gap of 9 mm

Undulator Type	Undulator Period (mm)
Planar	20.3
APPLE II	24.3
APPLE III	21.4
DELTA	19.9

For all of these undulator periods the required energies to achieve desired wavelengths are calculated (see Table 2).

Table 2: Energy values for different undulator types.

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

As it is already mentioned in the introduction the maximal achieved wavelength at FLASH 1 is 1.25 GeV and so one needs significant energy upgrade to achieve 1.3 and 1.5 nm wavelengths which we do not find realistic in near future.

3.1 Tunability

For the FELs with fixed-gap undulators the only method to change the radiation wavelength is to change the electron bunch energy, whereas for the varying-gap undulators that can be achieved by changing the gap of the undulator and hence by changing the undulator strength. Here we discuss tunability of the FEL with a varying-gap undulator. To achieve factor of 2 tunability we need to change the undulator gap so that the new undulator strength K_{rms2} satisfy the condition below (obtained from Eq. (1)):

$$\frac{\lambda_1}{\lambda_2} = \frac{1 + K^2_{\mathrm{rms1}}}{1 + K^2_{\mathrm{rms2}}} = 2. \tag{4}$$

As it is already mention the smaller the undulator gap, the bigger the undulator strength which means that by opening the undulator gap one will have increased strength. Therefore one can conclude from the Eq. 4 that K_{rms1} is bigger than K_{rms2} and that K_{rms1} corresponds to the gap of 9 mm which is the minimal possible gap for the reason already explained. We want to investigate the possibility to achieve factor of two tunability by opening the undulator gap so that the undulator strength became $K_{rms2} = 1/\sqrt{2}$. It is easy to note from Eq. 4 that $K_{\mathrm{rms1}} = \sqrt{2}$. We calculate the undulator periods which are required to obtain $K_{\mathrm{rms}} = \sqrt{2}$) with the undulator gap of 9 mm. Then we calculate the necessary gaps to obtain the undulator strength of $1/\sqrt{2}$ for the undulator periods already calculated. Using expression (3) for the K parameter and taking into account that $K_{\mathrm{rms1}} = \sqrt{2}$ is achieved for $g_1 = 9mm$ (the smallest possible gap), one is able to easily obtain from Eq. 3 the Eq. 5 for 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 unreasonably big, so we will throw it away.

The Table 3 represents the discussed results.

Table 3: Undulator periods where $K_{\mathrm{rms}} = \sqrt{2}$ is obtained for $g = 9$mm gap and undulator gaps for the given periods to obtain $K_{\mathrm{rms}} = 1/\sqrt{2}$.

Undulator Type	Undulator Period (mm)	Required Gap (mm)
Planar	26.8	13.9
APPLE II	32.6	14.3
APPLE III	28.0	13.7
DELTA	25.9	13.3

The next step is to calculate the required energies to achieve the wavelengths in scope of our interest with the RMS undulator strength of $\sqrt{2}$ and the undulator periods from Table 3 (the results are in the Table 4).

Table 4: Energies to achieve the desired wavelengths with the RMS undulator strength of $\sqrt{2}$ and the undulator gap of 9 mm.

Undulator Type	1.3 nm (GeV)	1.5 nm (GeV)	2.6 nm (GeV)	3.0 nm (GeV)
Planar	2.84	2.65	2.01	1.87
APPLE II	3.13	2.92	2.21	2.06
APPLE III	2.91	2.71	2.06	1.91
DELTA	2.79	2.60	1.98	1.84

One can note from this table that the tunability is unrealizeable in near future since a significant energy upgrade is needed.

4 On the Idea of the Afterburner Scheme

Another approach to reach the mentioned above wavelengths is to use long undulator (we will refer to it as main undulator) tuned to 2.6 or 3.0 nm, then use the modulated electron bunch from this undulator in shorter undulator (later on - afterburner) tuned to 1.3 or 1.5 nm. The second harmonic microbunches will radiate coherently the fundamental frequency of the afterburner. Here we consider electron bunch with energy of 1.4 GeV (easy to achieve by changing some accelerating modules).

4.1 Generation of 1.5 and 1.0 nm Wavelengths

In the Figs. 1 and 2 the dependence of K_{rms} value on λ_{u} (eqn. (1)) and dependance of g on λ_{u} (Eqs. (1) and (3)) are represented.

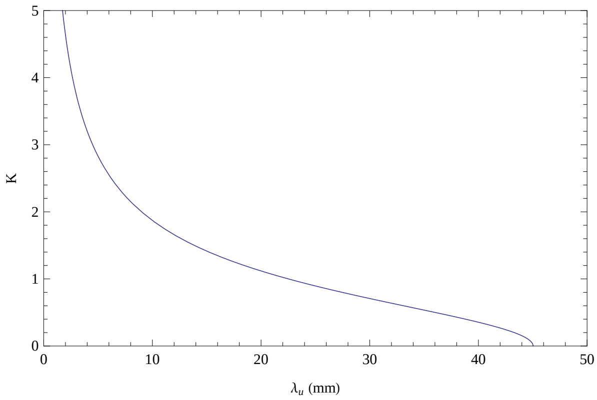


Figure 1: K versus λ_{u} needed to reach 3.0 nm at a bunch energy of 1.4 GeV in planar undulator.

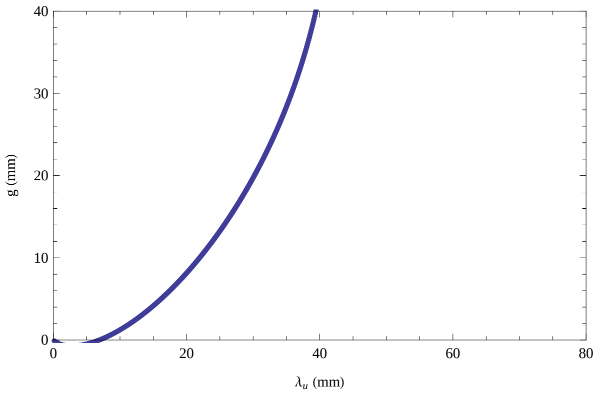


Figure 2: g versus λ_{u} needed to reach 3.0 nm at a bunch energy of 1.4 GeV in planar undulator.

K value and undulator period are calculated in case of radiation wavelength of 1.5 nm, bunch 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 discussed hitherto value of 9 mm is considered for safety reason, that is to have a flexibility on reaching relatively large wavelengths.

The same parameters for the 1.0 nm radiation (3$^{\mathrm{rd}}$ harmonic) are: $K = 0.1873$ and $\lambda_{\mathrm{u}} = 14.5$ mm.

4.2 Generation of 1.3 and 0.87 nm Wavelengths

In the Figs. (3) and 4 the dependence of K_{rms} value on λ_{u} (eqn. (1)) and dependance of g on λ_{u} (Eqs. (1) and (3)) are represented.

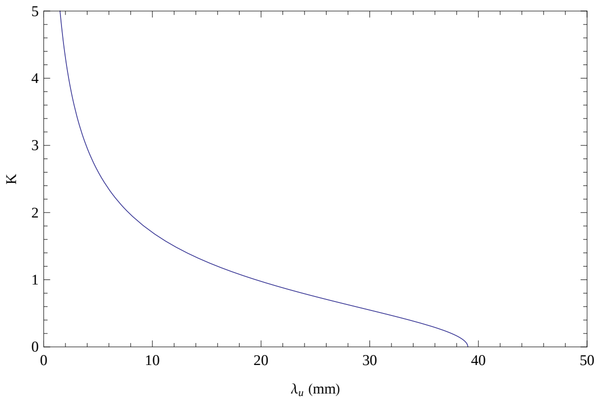


Figure 3: K versus λ_{u} needed to reach 2.6 nm at a bunch energy of 1.4 GeV in planar undulator.

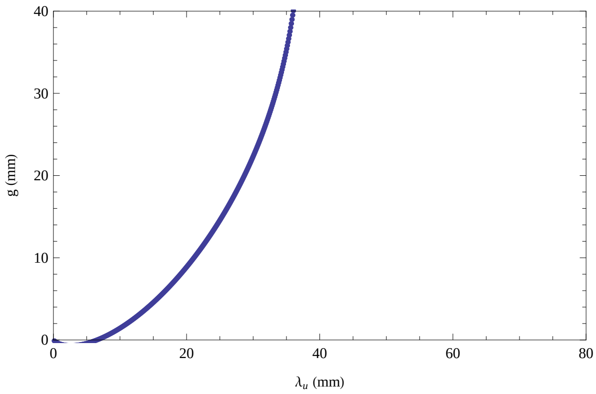


Figure 4: g versus λ_{u} needed to reach 2.6 nm at a bunch energy of 1.4 GeV in planar undulator.

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.

The same parameters for the 0.87 nm (3$^{\mathrm{rd}}$ harmonic) radiation are: $K = 0.1212$ and $\lambda_{\mathrm{u}} =$ 12.9 mm.

4.3 On the Idea of FLASH I as a Main Undulator

In this subsection we consider afterburner put after FLASH I. The undulator period of FLASH I is 27.3 mm and the undulator strength is 0.9. As it is easy to calculate from the Eq. 1 the required bunch energy to achieve 3.0 nm radiation with this undulator is 1.467 GeV. Assuming for the afterburner the gap to be 9.5 mm, one can calculate from Eqs. (3) and (1) (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 calculation for 1.0 nm wavelength generation leads to values: $K = 0.24$ and $\lambda_u = 15.6$ mm.

The same kind of calculation but now for reaching 2.6 nm radiation leads to the bunch energy of 1.575 GeV. Under the same assumption of the afterburner undulator gap to be 9.5 mm and by taking into account that the wavelength in the main undulator is changed just due to energy change, one can conclude that the afterburner parameters should stay the same as they were before the energy change.

4.4 On the Idea of FLASH II as a Main Undulator

In this subsection we consider afterburner put after FLASH II currently under construction. The undulator period of FLASH II is 31.4 mm. For comparison with FLASH I 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. Assuming for the afterburner the gap to be 9.5 mm, one can calculate from Eqs. (3) and (1) (for APPLE III undulator) that the required strength and undulator period to achieve 1.5 nm wavelength are $K = 0.505$ and $\lambda_{\mathrm{u}} = 19.7$ mm. The same calculation for 1.0 nm wavelength generation leads to values: $K = 0.24$ and $\lambda_{\mathrm{u}} = 15.6$ mm.

The same kind of calculation but now for reaching 2.6 nm radiation (as in case of FLASH I, the bunch energy is 1.575 GeV) leads to the undulator strength of 0.757. Under the same assumption of the afterburner undulator gap to be 9.5 mm and by taking into account that the wavelength in the main undulator is changed just due to energy change, one can conclude that the afterburner parameters should stay the same as they were before the energy change.

5 Genesis 1.3 Simulations

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 [4].

For each of the considered above option we performed two runs - first for the main undulator and the second for the afterburner. The main goal of the first run was to create an electron output file which then became an electron source for the second run.

5.1 Runs for Main Undulator 3.0 nm and its Harmonics

For the main undulator we consider two possibilities. First of them is to take the K_{rms} value to be $1/\sqrt{2}$. For this case one can see from the Fig. 1 that $\lambda_{\mathrm{u}} = 30.0$ mm. In the Fig. 5 the output power for this case is presented.

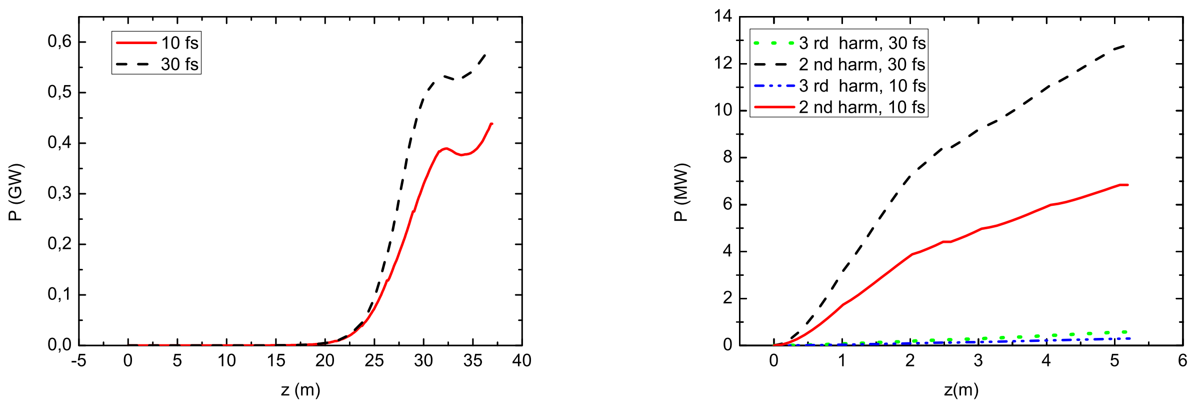


Figure 5: Main on the left and afterburner on the right. Radiation powers at 1.5 and 1.0 nm. Bunch energy is 1.4 GeV, $K_{rms}^{(main)} = 0.7070$ m, $\lambda_u^{(main)} = 0.03$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.4417$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0188$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.1873$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0145$ m.

The second possibility assumes a gap of $9mm$. From the Fig. 2 we can conclude that in this case the undulator period should be $\lambda_{\mathrm{u}} = 21$ mm. From the Fig. 1 it follows that the corresponding K value is 1.075.

In the Fig. 6 the output power for this case is presented.

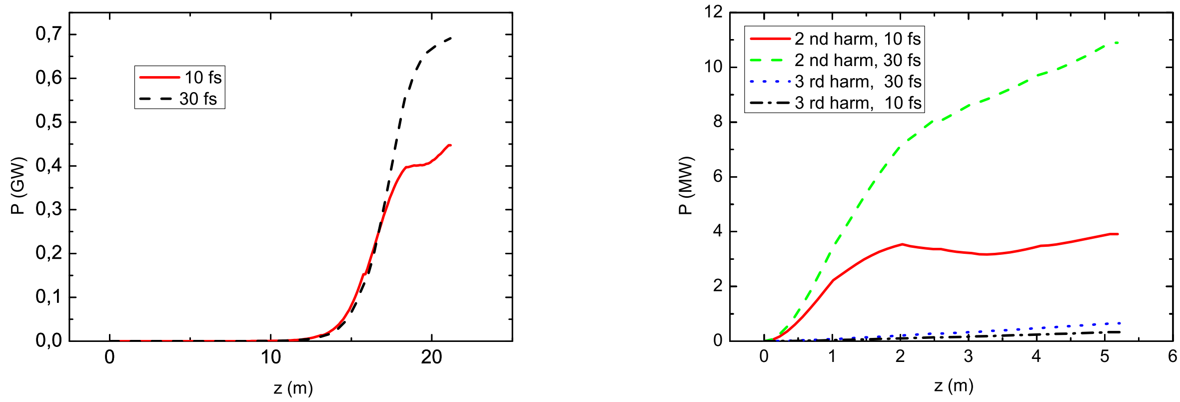


Figure 6: Main on the left and afterburner on the right. Radiation powers at 1.5 and 1.0 nm. Bunch energy is 1.4 GeV, $K_{rms}^{(main)} = 1.075$ m, $\lambda_u^{(main)} = 0.021$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.4417$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0188$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.1873$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0145$ m.

5.2 Runs for Main Undulator 2.6 nm and its Harmonics

For the main undulator we consider two possibilities. First of them is to take the K_{rms} value to be $1/\sqrt{2}$. For this case one can see from the Fig. 1 that $\lambda_\mathrm{u} = 26.0$ mm. In the Fig. 7 the output power for this case is presented.

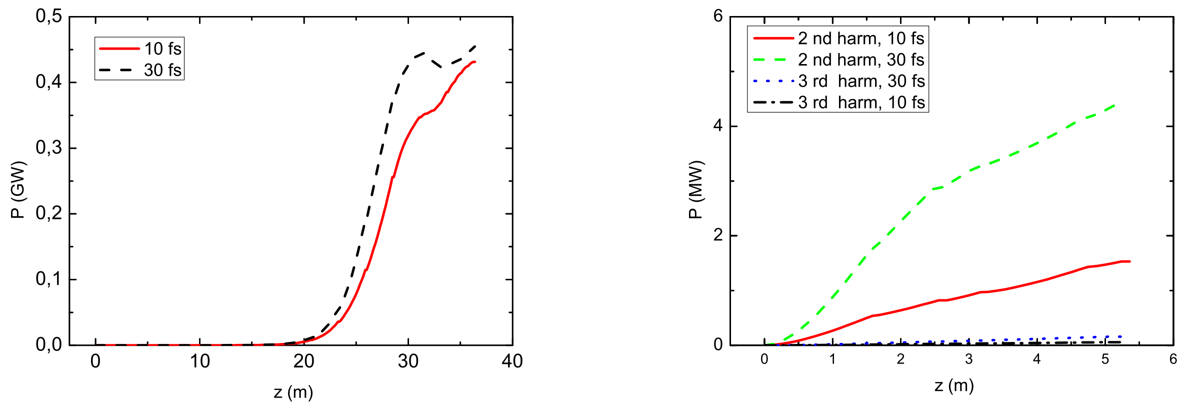
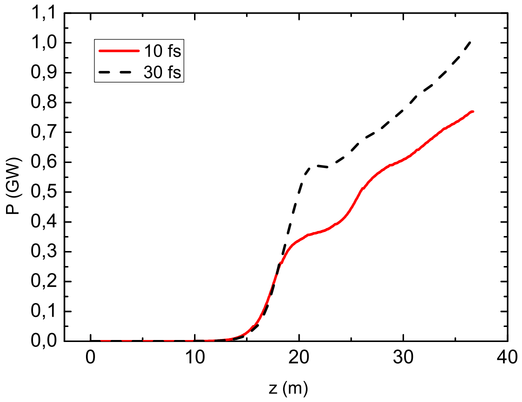


Figure 7: Main on the left and afterburner on the right. Radiation powers at 1.5 and 1.0 nm. Bunch energy is 1.4 GeV, $K_{rms}^{(main)} = 0.7$ m, $\lambda_u^{(main)} = 0.026$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.3464$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0174$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.1212$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0129$ m.

The second possibility assumes a gap of $9mm$. From the Fig. 4 we can conclude that in this case the undulator period should be $\lambda_\mathrm{u} = 20$ mm. From the Fig. 3 it follows that the corresponding K value is 0.9709.

In the Fig. 8 the output power for this case is presented.



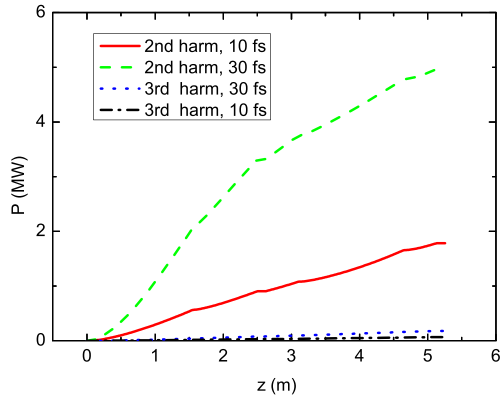
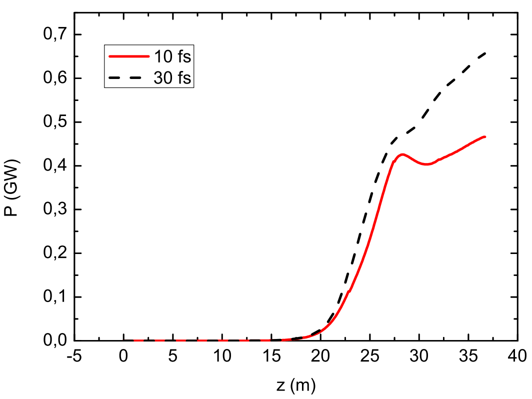


Figure 8: Main on the left and afterburner on the right. Radiation powers at 1.3 and 0.87 nm. Bunch energy is 1.4 GeV, $K_{rms}^{(main)} = 0.971$ m, $\lambda_u^{(main)} = 0.02$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.3464$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0174$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.1212$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0129$ m.

5.3 Simulation with FLASH I and FLASH II Parameters

The Figs. 9, 10, 11 and 12 show results of runs with FLASH 1 and FLASH 2 parameters.



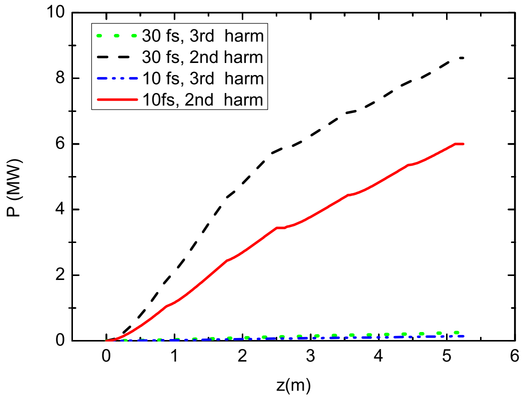


Figure 9: Main on the left and afterburner on the right. Radiation powers at 1.5 and 1.0 nm. Bunch energy is 1.467 GeV, $K_{rms}^{(main)} = 0.900$, $\lambda_u^{(main)} = 0.0273$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.505$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0197$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.24$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0156$ m.

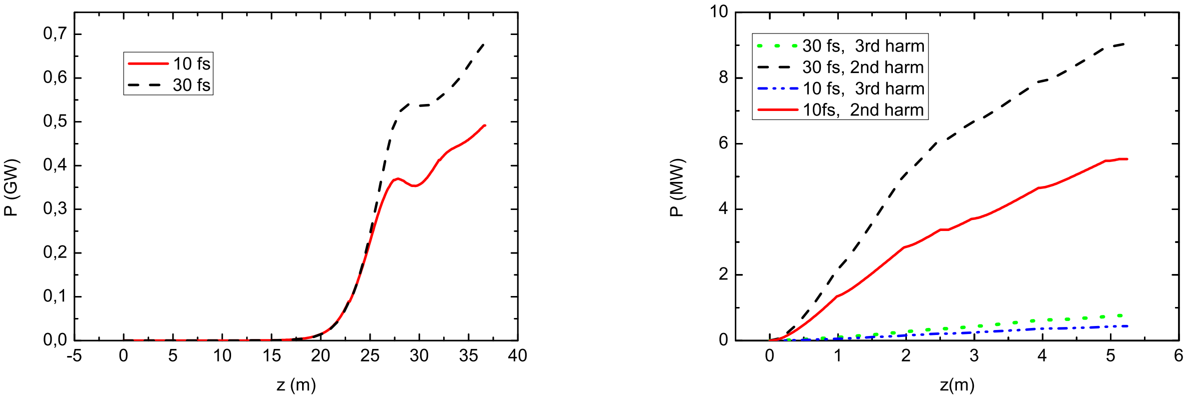


Figure 10: Main on the left and afterburner on the right. Radiation powers at 1.3 and 0.87 nm. Bunch energy is 1.575 GeV, $K_{rms}^{(main)} = 0.900$, $\lambda_u^{(main)} = 0.0273$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.505$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0197$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.24$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0156$ m.

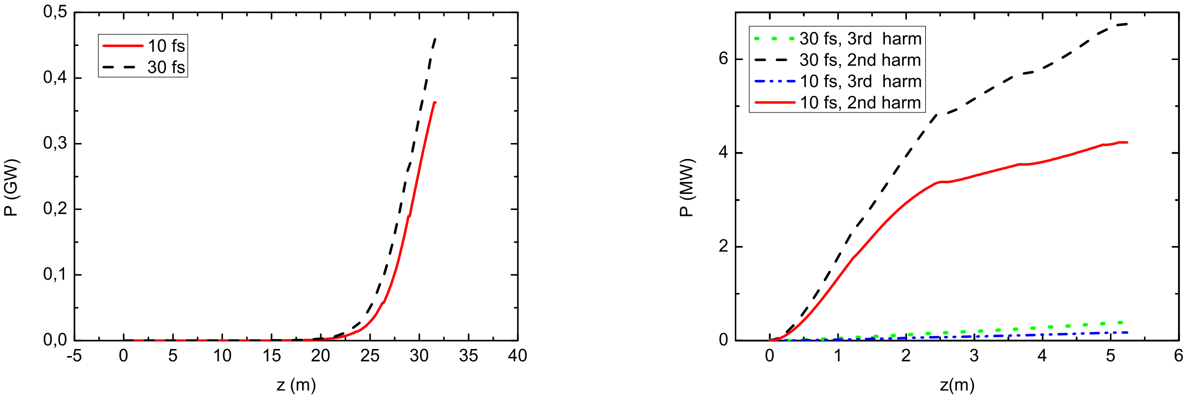


Figure 11: Main on the left and afterburner on the right. Radiation powers at 1.5 and 1.0 nm. Bunch energy is 1.467 GeV, $K_{rms}^{(main)} = 0.758$, $\lambda_u^{(main)} = 0.0314$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.505$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0197$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.24$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0156$ m.

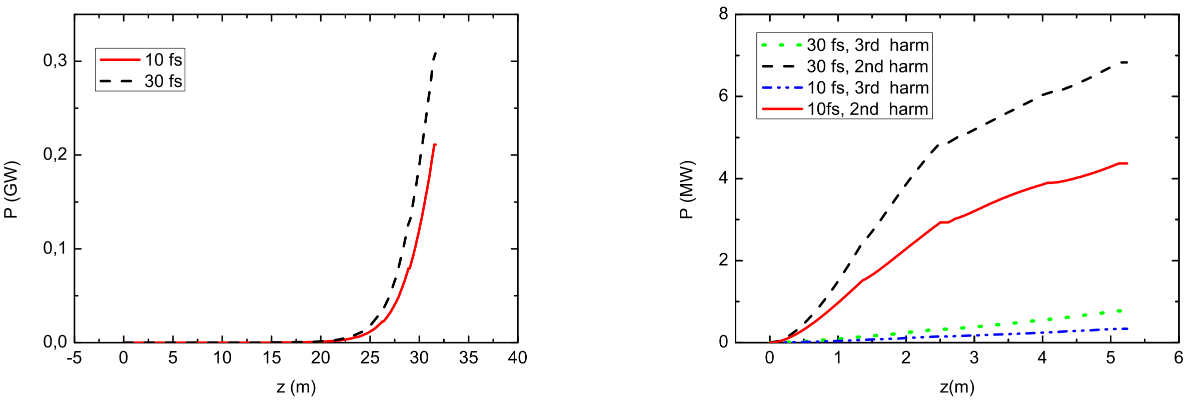


Figure 12: Main on the left and afterburner on the right. Radiation powers at 1.3 and 0.87 nm. Bunch energy is 1.575 GeV, $K_{rms}^{(main)} = 0.757$ m, $\lambda_u^{(main)} = 0.0314$ m. $K_{rms}^{(afterburner)2^{nd}harm} = 0.504$, $\lambda_u^{(afterburner)2^{nd}harm} = 0.0197$ m. $K_{rms}^{(afterburner)3^{rd}harm} = 0.24$, $\lambda_u^{(afterburner)3^{rd}harm} = 0.0156$ m.

6 Results

The simulation results are presented in the Tables 5 and 6 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). Hopefully further discussions of these results will follow.

Table 5: Results of time dependent genesis 1.3 simulations for 1.4 GeV electron bunch.

Simulation Parameters	Pulse Energy (μ J)	RMS Power (MW)	Pulse Length (fs)
2.6nm g9 mm 2nd harm end 30fs	1.184	13.61	86.98
2.6nm g9 mm 2nd harm mid 30fs	0.7799	8.674	89.91
2.6nm g9 mm 2nd harm end 10fs	0.2101	4.612	45.56
2.6nm g9 mm 2nd harm mid 10fs	0.1068	2.423	44.09
2.6nm g9 mm 3rd harm end 30fs	0.1713	0.6383	268.4
2.6nm g9 mm 3rd harm mid 30fs	0.07509	0.2815	266.8
2.6nm g9 mm 3rd harm end 10fs	0.05519	0.38	145.2
2.6nm g9 mm 3rd harm mid 10fs	0.0235	0.1659	141.6
2.6nm g9 mm main 10fs	67.22	1.739e+03	38.65
2.6nm g9 mm main 30fs	209.1	2.239e+03	93.37
2.6nm K0.7 2nd harm end 10fs	0.1823	5.86	31.11
2.6nm K0.7 2nd harm end 30fs	1.043	11.72	88.99
2.6nm K0.7 2nd harm mid 10fs	0.09809	2.687	36.51
2.6nm K0.7 2nd harm mid 30fs	0.6876	7.617	90.27
2.6nm K0.7 3rd harm end 10fs	0.04817	0.333	144.6
2.6nm K0.7 3rd harm end 30fs	0.1519	0.5672	267.8
2.6nm K0.7 3rd harm mid 10fs	0.02018	0.1421	142.0
2.6nm K0.7 3rd harm mid 30fs	0.06483	0.2431	266.7
2.6nm K0.7 main 10fs	39.94	1.076e+03	37.13
2.6nm K0.7 main 30fs	96.77	1.022e+03	94.67
3nm g9 mm 2nd harm end 10fs	0.3929	9.5	41.36
3nm g9 mm 2nd harm end 30fs	2.406	33.68	71.45
3nm g9 mm 2nd harm mid 10fs	0.3404	9.086	37.46
3nm g9 mm 2nd harm mid 30fs	1.778	23.12	76.91
3nm g9 mm 3rd harm end 10fs	0.08314	1.065	78.07
3nm g9 mm 3rd harm end 30fs	0.2406	1.454	165.4
3nm g9 mm 3rd harm mid 10fs	0.0335	0.4287	78.15
3nm g9 mm 3rd harm mid 30fs	0.1036	0.6256	165.7
3nm g9 mm main 10fs	39.01	1.106e+03	35.29
3nm g9 mm main 30fs	143.4	1.583e+03	90.56
3nm K0.7 2nd harm end 10fs	0.6872	19.24	35.71
3nm K0.7 2nd harm end 30fs	2.813	29.99	93.82
3nm K0.7 2nd harm mid 10fs	0.4135	12.17	33.99
3nm K0.7 2nd harm mid 30fs	1.86	18.73	99.34
3nm K0.7 3rd harm end 10fs	0.07323	0.9182	79.76
3nm K0.7 3rd harm end 30fs	0.2117	1.275	166.0
3nm K0.7 3rd harm mid 10fs	0.03081	0.3891	79.18
3nm K0.7 3rd harm mid 30fs	0.08283	0.499	166.0
3nm K0.7 main 10fs	39.52	1.086e+03	36.38
3nm K0.7 main 30fs	124.9	1.381e+03	90.45

Table 6: Results of time dependent genesis 1.3 simulations for FLASH I and FLASH II.

Simulation Parameters	Pulse Energy (μ J)	RMS Power (MW)	Pulse Length (fs)
FLASH1 2.6nm 2nd harm end 10fs	0.5119	12.02	42.59
FLASH1 2.6nm 2nd harm end 30fs	1.921	16.83	114.1
FLASH1 2.6nm 2nd harm mid 10fs	0.2906	6.827	42.57
FLASH1 2.6nm 2nd harm mid 30fs	1.309	12.41	105.5
FLASH1 2.6nm 3rd harm end 10fs	0.07471	1.141	65.48
FLASH1 2.6nm 3rd harm end 30fs	0.2212	1.467	150.8
FLASH1 2.6nm 3rd harm mid 10fs	0.03825	0.5864	65.23
FLASH1 2.6nm 3rd harm mid 30fs	0.1063	0.7069	150.4
FLASH1 2.6nm main 10fs	42.36	1.311e+03	32.31
FLASH1 2.6nm main 30fs	139.9	1.468e+03	95.34
FLASH1 3.0nm 2nd harm end 10fs	0.5623	13.14	42.79
FLASH1 3.0nm 2nd harm end 30fs	1.846	15.42	119.7
FLASH1 3.0nm 2nd harm mid 10fs	0.2921	6.891	42.39
FLASH1 3.0nm 2nd harm mid 30fs	1.253	11.01	113.8
FLASH1 3.0nm 3rd harm end 10fs	0.0241	0.3637	66.28
FLASH1 3.0nm 3rd harm end 30fs	0.07301	0.4798	152.2
FLASH1 3.0nm 3rd harm mid 10fs	0.01027	0.1551	66.18
FLASH1 3.0nm 3rd harm mid 30fs	0.03347	0.2218	150.9
FLASH1 3.0nm main 10fs	41.98	1.138e+03	36.88
FLASH1 3.0nm main 30fs	138.1	1.47e+03	93.92
FLASH2 2.6nm 2nd harm end 10fs	0.4581	13.79	33.22
FLASH2 2.6nm 2nd harm end 30fs	1.537	17.02	90.27
FLASH2 2.6nm 2nd harm mid 10fs	0.2733	8.698	31.42
FLASH2 2.6nm 2nd harm mid 30fs	1.065	11.41	93.28
FLASH2 2.6nm 3rd harm end 10fs	0.1127	1.238	91.08
FLASH2 2.6nm 3rd harm end 30fs	0.3498	1.909	183.2
FLASH2 2.6nm 3rd harm mid 10fs	0.03984	0.4372	91.13
FLASH2 2.6nm 3rd harm mid 30fs	0.1488	0.8092	183.9
FLASH2 2.6nm main 10fs	19.52	568.4	34.34
FLASH2 2.6nm main 30fs	65.62	819.8	80.04
FLASH2 3.0nm 2nd harm end 10fs	0.4501	11.88	37.9
FLASH2 3.0nm 2nd harm end 30fs	1.531	16.23	94.34
FLASH2 3.0nm 2nd harm mid 10fs	0.3321	9.556	34.75
FLASH2 3.0nm 2nd harm mid 30fs	1.023	11.19	91.43
FLASH2 3.0nm 3rd harm end 10fs	0.05866	0.638	91.95
FLASH2 3.0nm 3rd harm end 30fs	0.1759	0.9522	184.7
FLASH2 3.0nm 3rd harm mid 10fs	0.02042	0.2199	92.85
FLASH2 3.0nm 3rd harm mid 30fs	0.06707	0.3622	185.2
FLASH2 3.0nm main 10fs	34.26	1.091e+03	31.4
FLASH2 3.0nm main 30fs	98.6	1.095e+03	90.08

7 Acknowledgments

I would like to thank my supervisor Bart Faatz for introducing to me this interesting project and for many invaluable explanations, discussions and comments.

I would like also to thank Evgeny Saldin with whom I had a pleasure to discuss some theoretical aspects of FELs.

Many thanks to everyone why has contributed in organization of DESY SSP 2012.

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