

DEUTSCHES ELEKTRONEN-SYNCHROTRON

Ein Forschungszentrum der Helmholtz-Gemeinschaft

DESY 10-080

June 2010

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ISSN 0418-9833

NOTKESTRASSE 85 - 22607 HAMBURG

Cascade self-seeding scheme with wake monochromator for narrow-bandwidth X-ray FELs

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Abstract

Three different approaches have been proposed so far for production of highly monochromatic X-rays from a baseline XFEL undulator: (i) single-bunch self-seeding scheme with a four crystal monochromator in Bragg reflection geometry; (ii) double-bunch self-seeding scheme with a four-crystal monochromator in Bragg reflection geometry; (iii) single-bunch self-seeding scheme with a wake monochromator. A unique element of the X-ray optical design of the last scheme is the monochromatization of X-rays using a single crystal in Bragg-transmission geometry. A great advantage of this method is that the monochromator introduces no path delay of X-rays. This fact eliminates the need for a long electron beam bypass, or for the creation of two precisely separated, identical electron bunches, as required in the other two self-seeding schemes. In its simplest configuration, the self-seeded XFEL consists of an input undulator and an output undulator separated by a monochromator. In some experimental situations this simplest two-undulator configuration is not optimal. The obvious and technically possible extension is to use a setup with three or more undulators separated by monochromators. This amplification-monochromatization cascade scheme is distinguished, in performance, by a small heat-loading of crystals and a high spectral purity of the output radiation. This paper describes such cascade self-seeding scheme with wake monochromators. We present feasibility study and exemplifications for the SASE2 line of the European XFEL.

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1 Introduction

The self-seeding approach in Free-Electron Lasers (FELs) was proposed to obtain a bandwidth narrower than that achievable with conventional X-ray SASE schemes [1]-[5]. A self-seeded FEL consists of two undulators with a monochromator located between them. In the original VUV-soft X-ray case, a grating monochromator was proposed [6]. Three types of self-seeding schemes for hard X-ray FELs have been studied [7]-[10]. Historically, the first type was a single bunch self seeding scheme with a four-crystal monochromator in Bragg reflection geometry [7]. A second type was the double bunch self-seeding scheme with four crystal monochromator in Bragg reflection geometry [8, 9], and a third type was a single-bunch self-seeding scheme making use of a wake monochromator [10]. A unique element of the X-ray optical design of the last scheme is the monochromatization of X-rays using a single crystal in Bragg transmission geometry. The X-ray beam is transmitted through a thick crystal oriented for Bragg reflection. A great advantage of this method is that it introduces no path-delay of X-rays in the monochromator, thus avoiding the need for a long electron beam bypass, or for the creation of two precisely separated, identical electron bunches, as required in schemes with the monochromator in Bragg reflection geometry.

In [10] we discussed how such kind of self-seeding scheme may be combined with a fresh bunch technique [11]-[16]. The combination of self-seeding and fresh bunch techniques is extremely insensitive to noise and non-ideal effects. In fact, the radiation pulse used to produce the monochromatic (wake) seed signal is in the GW-level power. This large power can tremendously improve the signal-to-noise ratio of the self-seeding scheme. The possibility of combining self-seeding scheme and fresh bunch technique would be of great importance especially during the early experimental stage, when a proof of principle is built.

Despite of these advantages, the combination of self-seeding and fresh bunch techniques suffers from two drawbacks. First, there is a strong SASE signal outside of the seed bandwidth, due to application of fresh bunch technique². Second, the power of the SASE pulse which impinges on the crystal is relatively large and heat-loading problems are not automatically avoided. This is the case, in particular, when the combination of self-seeding and fresh bunch techniques is used at the European XFEL, which is characterized by a very high repetition rate. These drawbacks can be overcome by using the cascade self-seeding scheme proposed in the present work.

² Actually this can be transformed into an advantage. The SASE pulse can be separated from the longitudinally coherent seed pulse by the post monochromator in the experimental hall and exploited separately.

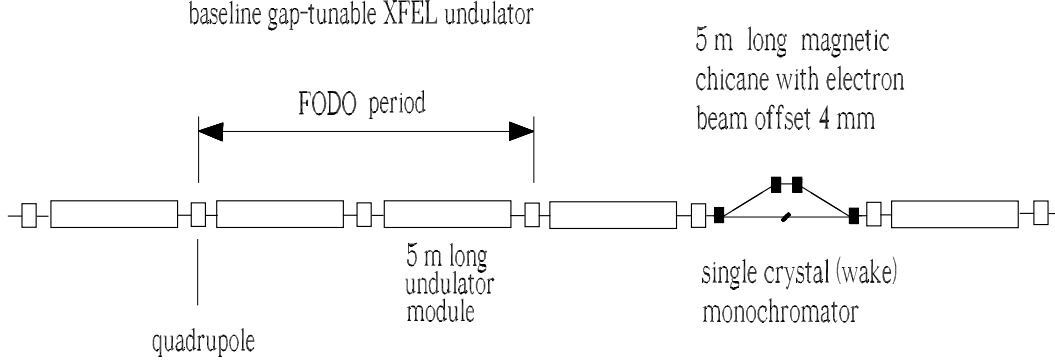


Fig. 1. Installation of a wake monochromator in the baseline XFEL undulator. The setup is composed of two components, a crystal and a weak magnetic chicane. The magnetic chicane accomplishes three tasks by itself. It creates an offset for crystal installation, it removes the electron micro-bunching produced in the upstream undulator, and it acts as a delay line for temporal windowing. The transmittance spectrum of the crystal shows a narrow-band absorption resonance when the incident X-ray beam satisfies the Bragg diffraction condition. The temporal waveform of the transmitted radiation pulse is characterized by a long monochromatic wake. After the crystal, the monochromatic wake of the radiation pulse is combined with the delayed electron bunch, and amplified in the downstream undulator.

In this paper we study such scheme, which consists of two parts: a succession of two amplification-monochromatization cascades and an output undulator in which the monochromatic seed signal is amplified up to saturation. Each cascade consists of an undulator, acting as an amplifier, and a monochromator.

In the next section we describe in detail the method and the basic principles of our technique. Subsequently, in the following sections, we study the feasibility of the technique, giving exemplification for the SASE2 beamline at the European XFEL.

2 Principle of cascade self-seeding techniques based on the use of wake monochromators

The self-seeding technique considered in this work is based on the substitution of a single undulator module with a weak chicane and a single crystal,

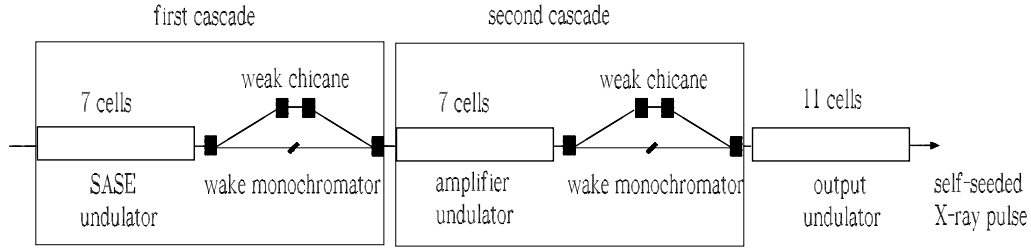


Fig. 2. Design of an undulator system for narrow-bandwidth mode of operation. The scheme is based on the use of a cascade, single bunch self-seeding scheme with wake monochromators. In performance, the cascade type of self-seeded XFEL is distinguished by its small heat-loading of monochromators.

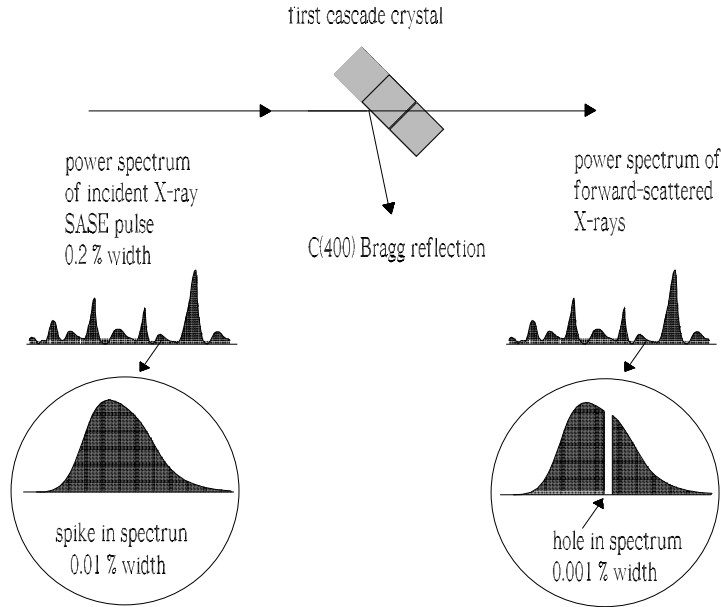


Fig. 3. First cascade. Short pulse mode of operation. The crystal acts as a bandstop filter for the transmitted X-ray SASE radiation pulse.

as shown in Fig. 1. Two cascades can be arranged sequentially as shown in Fig. 2. In this paper we will consider both the case when a single cascade or two cascades are present. With reference to Fig. 2, we begin to study the case when two-cascades are present.

The first undulator in Fig. 2 operates in the linear high-gain regime starting from the shot-noise in the electron beam. After the first undulator, the output SASE radiation passes through the monochromator, which reduces the bandwidth to the desired value. According to the wake monochromator principle, the SASE pulse coming from the first undulator impinges on a crystal set for Bragg diffraction. Then, the single crystal in Bragg geometry actually operates as a bandstop filter for the transmitted X-ray SASE radiation pulse, as shown in Fig. 3. When the incident angle and the spectral contents of the incoming beam satisfy the Bragg diffraction condition, the temporal waveform of the transmitted radiation pulse shows a long monochromatic wake. The duration of this wake is inversely proportional to the bandwidth of the absorption line in the transmittance spectrum.

While the radiation is sent through the crystal, the electron beam passes through a magnetic chicane, which accomplishes three tasks by itself: it creates an offset for the crystal installation, it removes the electron micro-bunching produced in the first undulator, and it acts as a delay line for the implementation of the temporal windowing. In other words, the magnetic chicane shifts the electron bunch on top of the monochromatic wake created by the bandstop filter thus selecting (temporal windowing) a part of the wake. By this, the electron bunch is seeded with a radiation pulse characterized by a bandwidth much narrower than the natural FEL bandwidth.

For the hard X-ray wavelength range, a small dispersive strength R_{56} in the order of ten microns is sufficient to remove the micro bunching in the electron bunch. As a result, the choice of the strength of the magnetic chicane only depends on the delay that we want to introduce between electron bunch and radiation. In our case, this amounts to $6\text{ }\mu\text{m}$ for the short pulse mode of operation and to $60\text{ }\mu\text{m}$ for the long pulse mode of operation. Such dispersion strength is small enough to be generated by a short 5 m-long chicane to be installed in place of a single undulator module. Such chicane is, however, strong enough to create a sufficiently large transverse offset of a few millimeters for installing the crystal.

Successful operation of the self-seeded XFEL requires fulfillment of several requirements. The first undulator must operate in the deep linear regime, and not in saturation. In fact, the amplification process in the FEL leads to an energy modulation in the electron beam. After the electron beam passes through the magnetic chicane, such energy modulation transforms into additional energy spread. Calculations show that in order not to spoil the electron beam quality, the power gain of the first undulator should be about three orders of magnitude smaller than the power gain of the X-ray SASE FEL at saturation. Here we consider the hard X-ray mode of operation, where the effective power of shot-noise in the electron beam is $P_n \sim 3\text{ kW}$, and the power of the SASE radiation at saturation is $P_{\text{sat}} \sim 30\text{ GW}$. It follows

that for effective operation of the second undulator, one requires that the power gain of the first undulator be no more than four orders of magnitude.

To provide effective operation of the self-seeded XFEL, we also require that the power of the monochromatic seed signal P_{seed} at the entrance of the output undulator significantly exceeds the effective shot-noise power in the electron beam, i.e. $P_{\text{seed}} \gg P_n$. Calling G_1 the power gain in the first undulator, and T_m the transmission factor of the monochromator one has $P_{\text{seed1}}/P_n \sim G_1 T_m$. For a bandpass filter the transmission factor is simply the ratio of the of the transmitted pulse power to the incoming pulse power. Similarly, for the wake monochromator we can define T_m as the ratio of the wake power in the temporal window defined by the electron bunch length to the incoming pulse power. More in detail, T_m can be written the product of a geometrical factor R_m and a coefficient K_s , i.e. $T_m \sim R_m K_s$. The geometrical factor R_m depends on the line width of the bandstop filter, $\Delta\omega_m$, and on the time delay τ_d , while the coefficient K_s can be written in the form $K_s \sim \Delta\omega_m/(\Delta\omega_{in})$, where $\Delta\omega_{in}$ is the bandwidth of the incoming X-ray beam. Using only a single cascade, i.e. considering the simplest possible two-undulator configuration of the self-seeded XFEL, the bandwidth of the incoming beam is actually the radiation bandwidth of the SASE XFEL i.e. $\Delta\omega_{in} \sim \Delta\omega_{\text{SASE}}$. Our calculations (see the next Sections) show that in this case the transmission factor for the wake monochromator is about 0.1%. Remembering that $P_{\text{seed1}}/P_n \sim G_1 T_m$, and that $G_1 \lesssim 10^4$, one cannot fulfill the requirement $P_{\text{seed1}} \gg P_n$. In [10] we proposed a method to get around this obstacle. It is based on the application of the self-seeding scheme with wake monochromator described above in combination with a fresh bunch technique. At variance, here we propose a new method to increase the value of P_{seed} . A high value of the signal-to-noise ratio at the entrance of the output undulator may in fact be obtained by using more than one stage of amplification-monochromatization.

Consider the three-undulators self-seeding scheme (i.e. two cascades) as shown in Fig. 2. To be specific, here we consider the case of two identical cascades. As discussed above, the signal-to-noise ratio at the entrance of the second undulator cannot be much larger than unity. Nevertheless, the monochromatic field amplitude at the entrance of the third undulator will be much larger than that at the entrance of the second. The difference with respect to the previously discussed two-undulator configuration is that after amplification in the second undulator, Fig. 4, the bandwidth of the X-ray pulse related with the monochromatic signal that impinges on the second crystal is near to the transform-limited bandwidth of the electron bunch i.e. c/σ_e . In other words, the transmission factor is now $T_m = R_m \Delta\omega_m c/\sigma_e$. As a result, assuming the same amplification $G_2 = G_1$, the signal to noise ratio is enhanced by a factor given by the ratio of the two transmission factors, i.e. $\sigma_e \Delta\omega_{\text{SASE}}/c$. A rough estimate for the signal to noise ratio at the entrance of

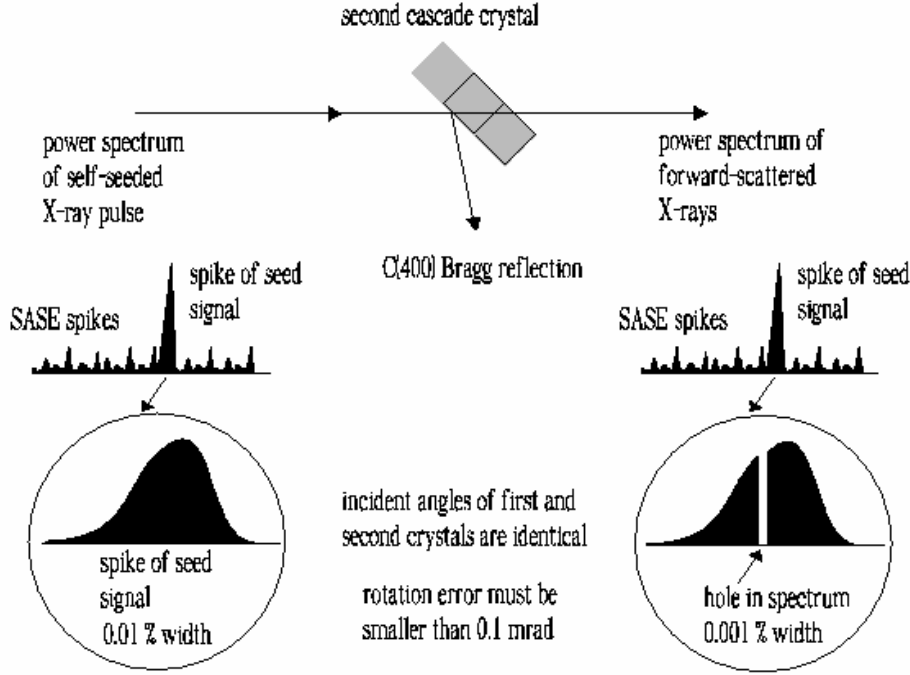


Fig. 4. Second cascade. The crystal acts as a bandstop filter for the self-seeded X-ray pulse. The incident angles of first and second crystals are identical. The rotation error must be smaller than 0.1 mrad for the short pulse mode of operation.

the third (output) undulator is therefore $P_{\text{seed2}}/P_n \sim (P_{\text{seed1}}/P_n)\sigma_e\Delta\omega_{\text{SASE}}/c \gg 1$. Since this value is much larger than unity, we conclude that a double cascade self-seeding scheme using a wake monochromator is insensitive to noise and non-ideal effects.

It should be noted that the three-undulator configuration in Fig. 2 can be naturally taken advantage of in different schemes, as shown in Fig. 5. The upper figure (a) shows the present self-seeding scheme. The middle figure (b) refers to the self-seeding scheme in combination with the fresh-bunch technique, as discussed in [10]. Finally, the lower figure (c) shows the advantage of a two-chicane setup when dealing with pump-probe techniques. In this case, as considered in [14], the first chicane enforces a fresh bunch technique and prepares a radiation pulse of a given color while, the second can be used to delay the electron bunch relative to such pulse, to obtain a tunable delay. The three above-mentioned setups are now combined in a single unit composed by three undulators equipped with two wake monochromators.

Finally, it is interesting to briefly discuss the simpler two-undulator configuration, Fig. 6. The two-undulator configuration may be particularly advantageous in cases when the total available undulator length is too short

flexibility of cascade self-seeding setup installed in baseline XFEL undulator with tunable gap

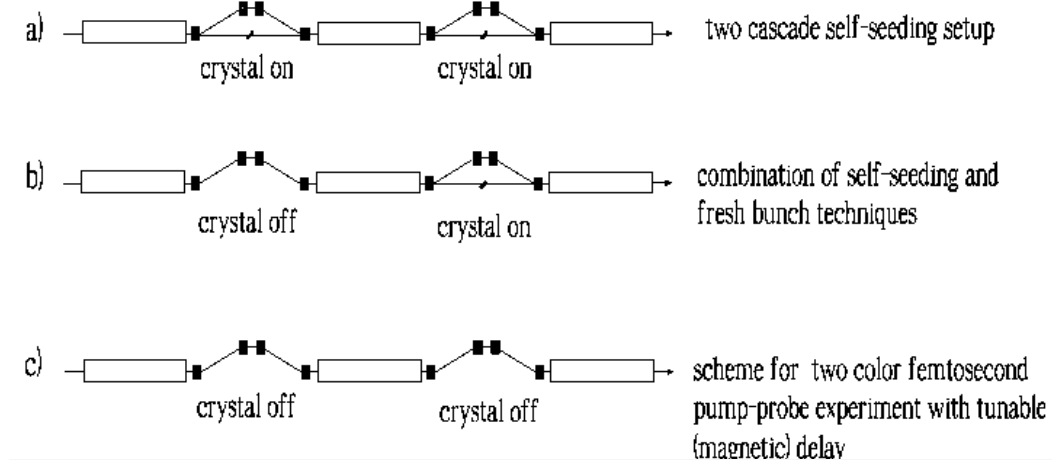


Fig. 5. Three modes of operation for the two weak magnetic chicanes installed in the XFEL baseline undulator with tunable gap are foreseen.

to enforce the three-undulator configuration. In this case, one may consider an increase in length of the first undulator in order to increase the contrast between seeded and SASE signal, at the cost of increasing the heat load.

As discussed above, in the two-undulator configuration, even if the instantaneous powers of seed signal and SASE noise are comparable, in the Fourier domain there is an enhance in photon spectral density order of $\sigma_e \Delta \omega_{SASE} / c \gg 1$, because of the different spectral widths of seed and SASE noise. As a result, even though we have no spectral purity, in the case of two-undulator configuration the spectral density is still comparable with the three-undulator configuration. If it is possible to use a post-monochromator to filter out the SASE signal, a user will obtain a radiation source with characteristics comparable to the three-undulator configuration, with larger fluctuations and a few times smaller brightness. Spectral purity can be, however, of crucial importance for application of some other techniques like tapering and polarization manipulations, i.e. for the next steps of performance improvement.

3 Heat Loading issues

In a previous paper of us [10] we proposed to couple the monochromatization through a wake monochromator with a fresh-bunch technique. As

two undulator configuration

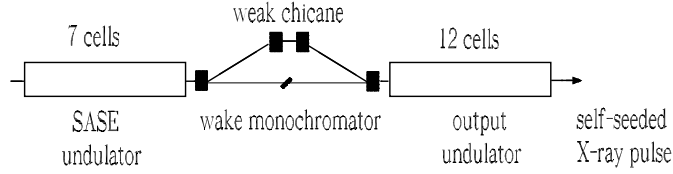


Fig. 6. Self-seeding setup with wake monochromator. Two undulator configuration. Short pulse mode of operation. Compared with the two cascade case, where almost all photons radiated within the seed bandwidth, here there is strong output SASE radiation outside this bandwidth.

noted above, this solution has advantages in terms of high signal to noise ratio, but also disadvantages, among which the presence of off-band SASE radiation, and a high heat-load of the monochromator crystal. For the European XFEL, the combination of our self-seeding scheme with a fresh bunch technique, as proposed in [8], satisfies the heat loading restrictions for the average power density. In fact, we showed that the situation is not different compared to third generation sources. However, the European XFEL differs compared to third generation sources in the very specific time diagram, which foresees the production of about 10 trains of pulses per second, each train consisting of about 3000 pulses. In this case, the average power density along a single pulse-train is the meaningful figure of merit, rather than the above-mentioned average power density.

The two-cascade setup drastically relaxes the heat load on the crystals, and eliminates the presence of the off-band SASE radiation, still retaining the advantage of a high signal to noise ratio. The energy per bunch impinging on the second crystal, which bears the largest heat-load, can be estimated as 150 nJ for the short bunch ($1\mu\text{m}$) mode of operation and $1.5\mu\text{J}$ for the long bunch ($10\mu\text{m}$) mode of operation (see Section 4, Fig. 16 and Section 5, Fig. 30). Let us consider the long-bunch mode of operation, which poses the most difficult challenge. From the previous numbers, one can easily estimate an average power of 50 mW ($1.5\mu\text{J} \times 3000 \text{ pulses/train} \times 10 \text{ trains/s}$).

This corresponds to a normal incident power density³ of $20\text{W}/\text{mm}^2$ at the position of the second monochromator, already an order of magnitude smaller compared with the average power density at monochromators of third generation synchrotron sources.

The average power within a single bunch train can be estimated by multiplying the energy by about $3 \cdot 10^3$ pulses composing a single train and dividing by the temporal duration of a train, which is 0.6 ms. One obtains a maximum power (for the long bunch mode of operation) of 7.5 W. Considering a transverse rms bunch dimension of about $20\mu\text{m}$, as before, we obtain a power density of about $3\text{ kW}/\text{mm}^2$ within a single train, at normal incidence. Such heat-load is orders of magnitude smaller than what is foreseen at monochromators for the baseline SASE2, where a diamond crystal with the same thickness (0.1 mm) is planned to be used.

4 Feasibility study for a short bunch

Following the previous introduction of the proposed methods we report on a feasibility study of the single-bunch self-seeding scheme. This feasibility study is performed with the help of the FEL code GENESIS 1.3 [17] running on a parallel machine. In this section we will present the feasibility study for the short-pulse mode of operation ($1\mu\text{m}$ rms) while, later on, we will cover the long-pulse mode of operation ($10\mu\text{m}$ rms). We will treat both the two-undulator as well as the three-undulator configuration. Parameters used in the simulations for the short pulse mode of operation are presented in Table 1. For the long pulse mode of operations Table 1 is still valid, except for a ten times larger charge (0.25 nC) and a ten times longer rms bunch length. We present a statistical analysis consisting of 100 runs for both short and long pulse mode of operation.

³ We consider a transverse rms dimension of the bunch of about $20\mu\text{m}$. Assuming, with some approximation, that radiation is distributed as the electron bunch, we obtain an area of $2.4 \cdot 10^{-3}\text{mm}^2$.

Table 1
Parameters for the short pulse mode of operation used in this paper.

	Units	
Undulator period	mm	48
K parameter (rms)	-	2.516
Wavelength	nm	0.15
Energy	GeV	17.5
Charge	nC	0.025
Bunch length (rms)	μm	1.0
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

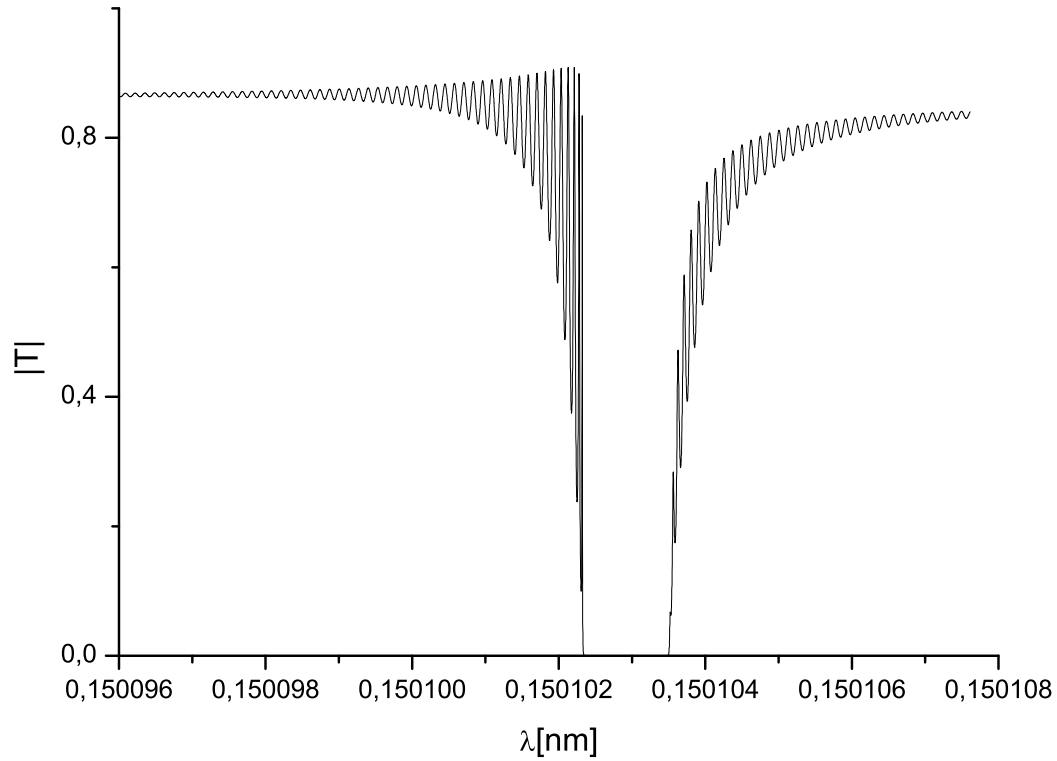


Fig. 7. Transmissivity (sigma polarization) relevant to the Bragg 400 diffraction of X-rays at 0.15 nm from a Diamond crystal with a thickness of 0.1 mm.

4.1 Two-undulator configuration

After the first seven cells (42 m) the electron bunch is sent through the weak chicane, while radiation is filtered through a single diamond crystal. Here we use the C(400) Bragg reflection and we assume, as said before, that the crystal has a thickness of 0.1 mm. The modulus and phase of the

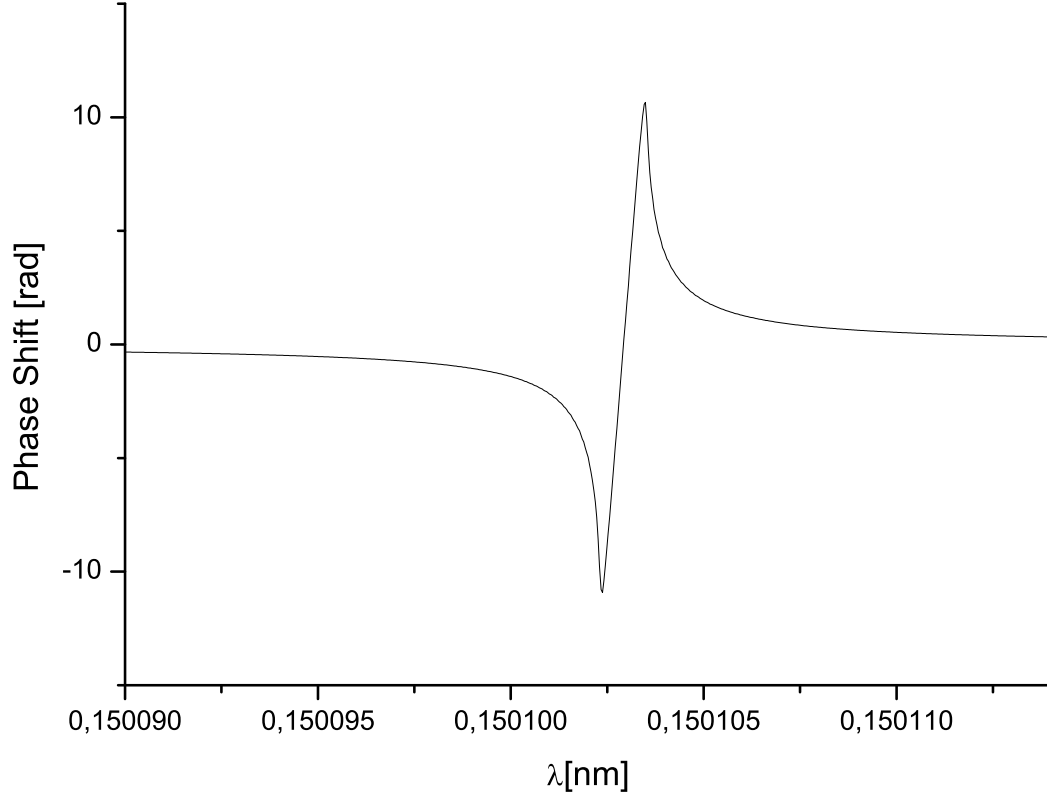


Fig. 8. Minimal phase shift of the forward-diffracted X-rays at 0.15 nm (sigma polarization) relevant to the Bragg 400 diffraction from a Diamond crystal with a thickness of 0.1 mm.

transmissivity function for the sigma-polarization component are shown in Fig. 7 and Fig. 8, and were calculated as described in [10]. The profile of the radiation before the filter is shown in Fig. 9.

As discussed above, and explained in detail in [10], the crystal acts as a bandstop filter. The effect is best shown by a comparison of the spectra before and after the filter, Fig. 10. Monochromatization does not take place in the frequency domain. At first glance, the passage through the bandstop filter is only responsible for slight change in the power distribution along the pulse. However, a zoom of the vertical axis shows what we are interested in: a long, monochromatic tail in the power distribution on the left side of the picture, Fig. 11.

Following the first crystal, we consider two alternative schemes. First, a two-undulator configuration, where the radiation from the first crystal is used to seed the electron bunch in an output undulator and, second, a three-undulator configuration where two monochromatization cascades are foreseen. Let us first consider the two-undulator configuration.

With reference to Fig. 6, we optimized the length of the output undulator

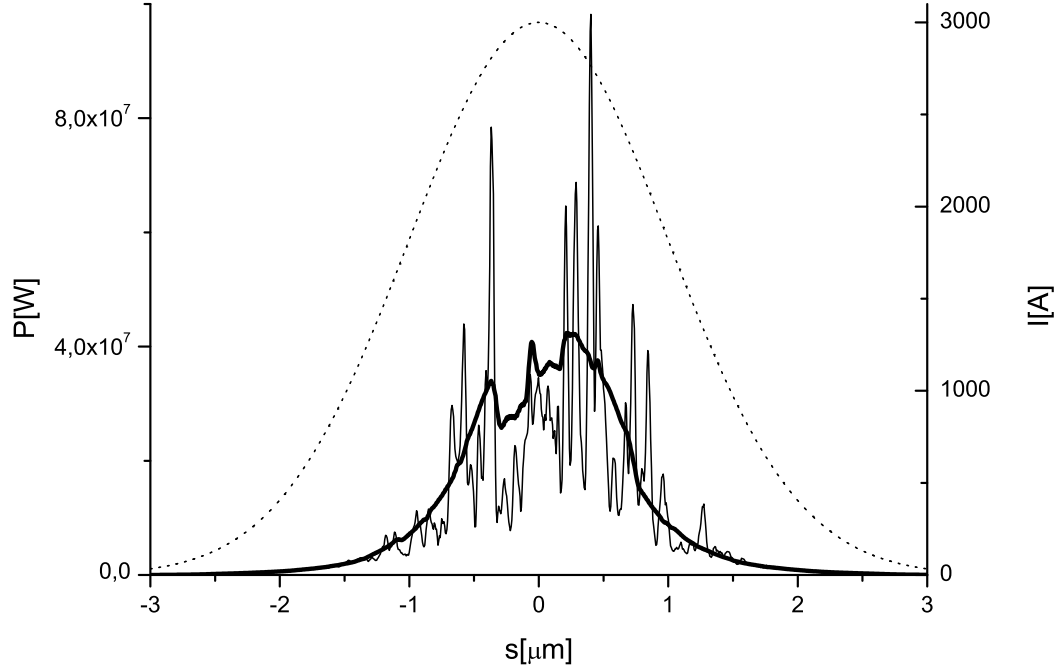


Fig. 9. Short pulse mode of operation. Input power at the crystal, at the end of the first undulator, 7 cells long (42 m). The average input power is represented with a solid thick line. A typical shot is also shown with a solid thin line. The dashed line illustrates the corresponding distribution of the electron beam current.

to obtain maximal spectral power. The optimal length is found to be 12 cells. In Fig. 12 and Fig. 13 we show, respectively, the average energy of the pulse as a function of the undulator length, and the rms deviation from the average⁴. Fig. 14 and Fig. 15 show, instead, the output power and spectrum. An estimation of the SASE contribution can be done by evaluating the total power outside the spectral window shown with black straight lines in Fig. 15 and dividing it by the total power in the pulse. Such ratio is about 14%. Obviously there is some ambiguity in the definition of the spectral window. Nevertheless, the ratio is weakly dependent on the choice of the window width and one can take the over-mentioned figure as a rough estimation of the SASE contribution to the total pulse.

⁴ As one may see, at the beginning of the undulator the fluctuations of energy per pulse apparently drop, see Fig. 13. This can be explained considering the fact that the Genesis output consists of the total power integrated over the full grid up to an artificial boundary, i.e. there is no spectral selection. Therefore, our calculations include a relatively large spontaneous emission background, which has a much larger spectral width with respect to the amplification bandwidth and which fluctuates negligibly from shot to shot. Since there is a long lethargy of the seeded radiation at the beginning of the FEL amplifier, one observes an apparent decrease of fluctuations. Then, when lethargy ends, the seed pulse gets amplified and fluctuations effectively return to about the same level as after monochromator.

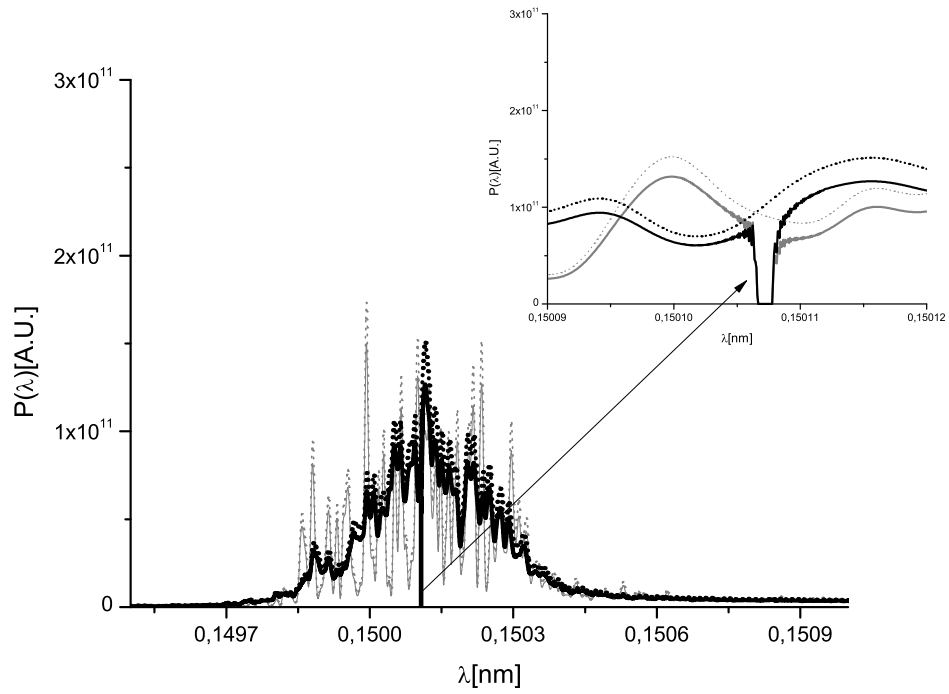


Fig. 10. Short pulse mode of operation. Average output spectrum after the diamond crystal and typical shot (solid thick line and solid thin line respectively). The bandstop effect is clearly visible, and highlighted in the inset. For comparison, the average spectrum before the diamond crystal and a typical shot (dotted thick line and dotted thin line respectively) is also shown.

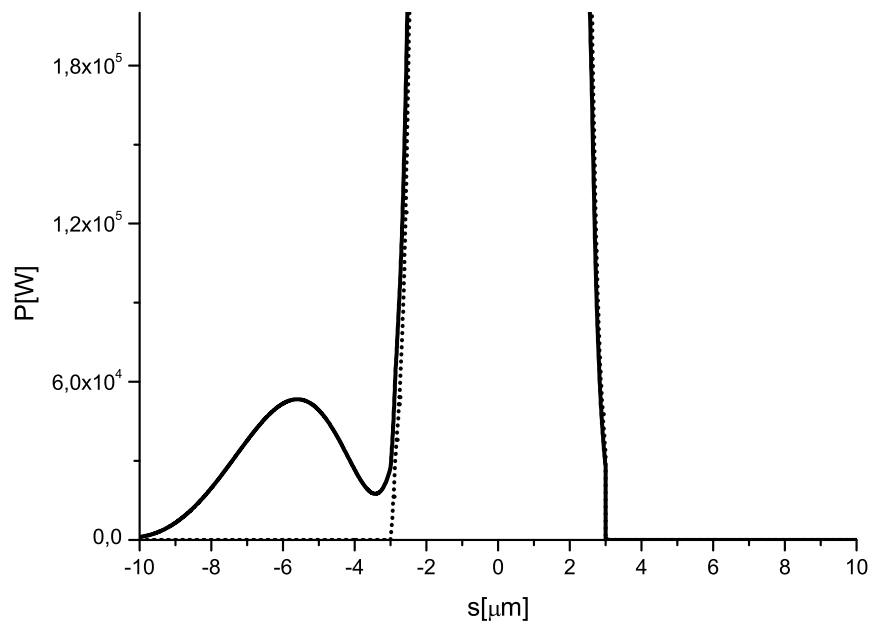


Fig. 11. Short pulse mode of operation. Power distribution before (dotted line) and after (solid line) transmission through the crystal. The monochromatic tail due to the transmission through the bandstop filter is evident on the left of the figure.

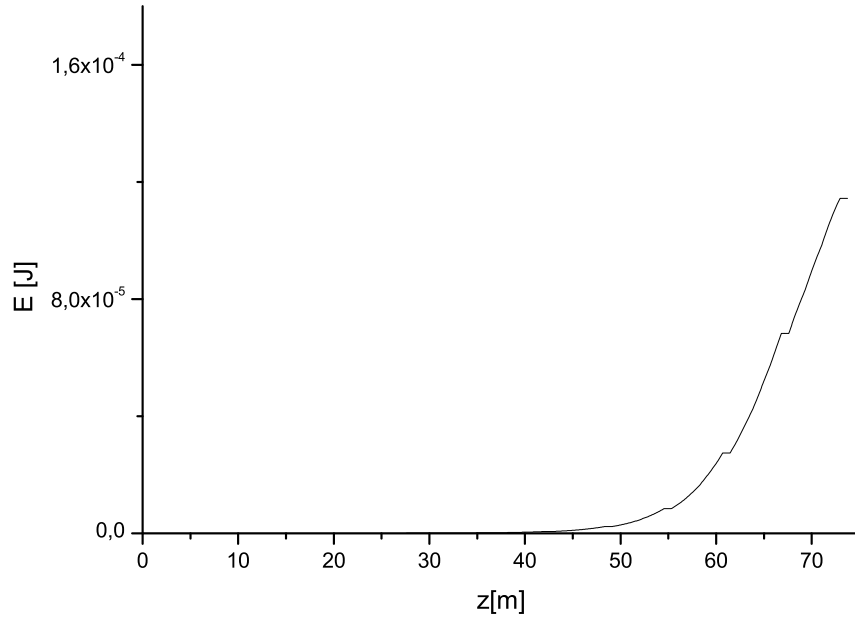


Fig. 12. Two-undulator configuration. Short pulse mode of operation. Average energy of the radiation pulse as a function of the second undulator length.

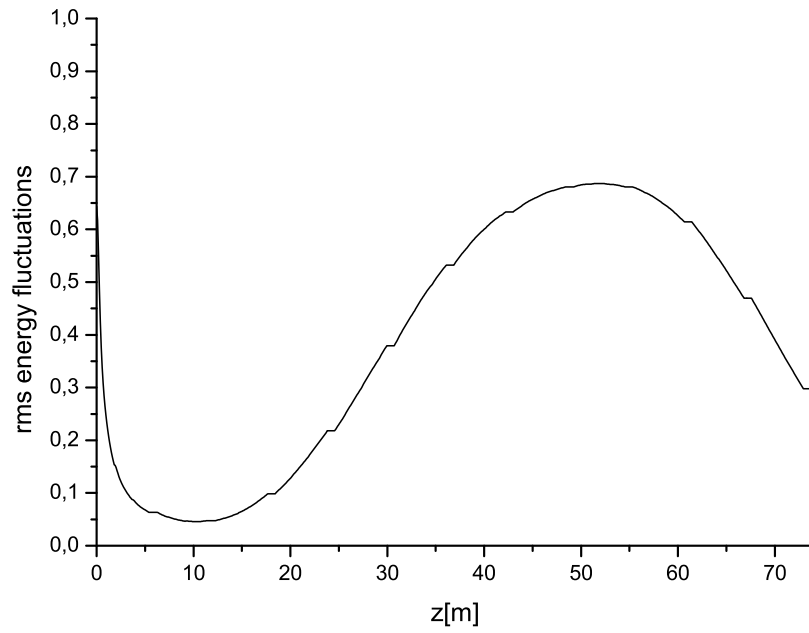


Fig. 13. Two-undulator configuration. Short pulse mode of operation. rms energy deviation from the average as a function of the second undulator length.

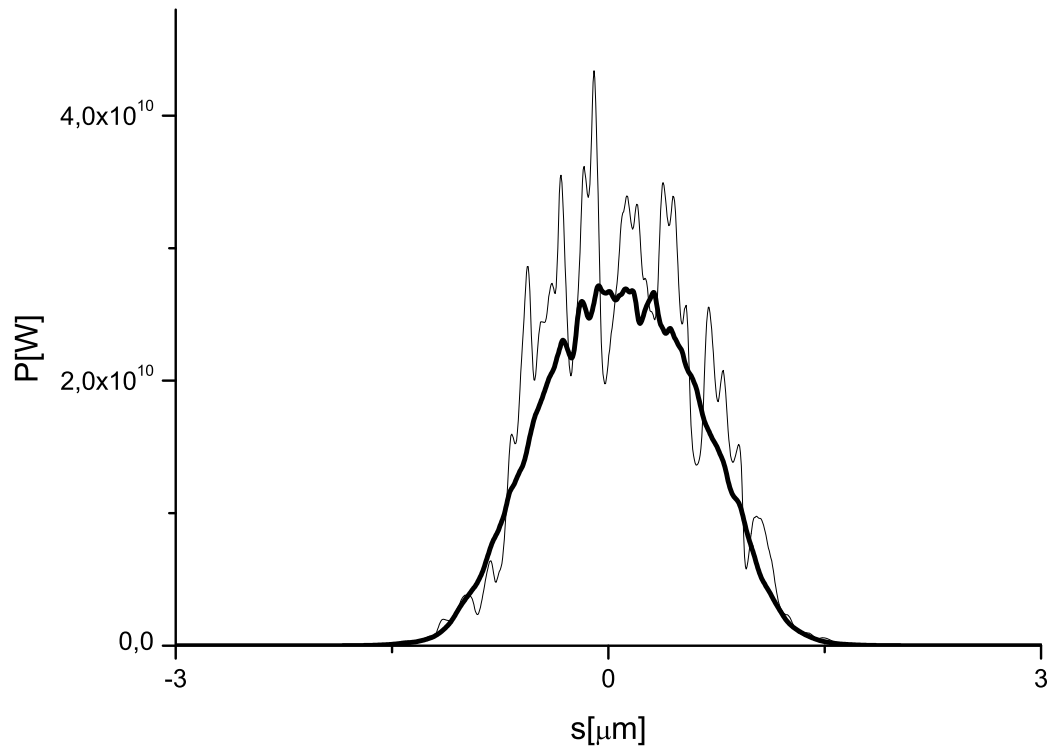


Fig. 14. Two-undulator configuration. Short pulse mode of operation. Average and typical single-shot output power (respectively, thick and thin solid lines).

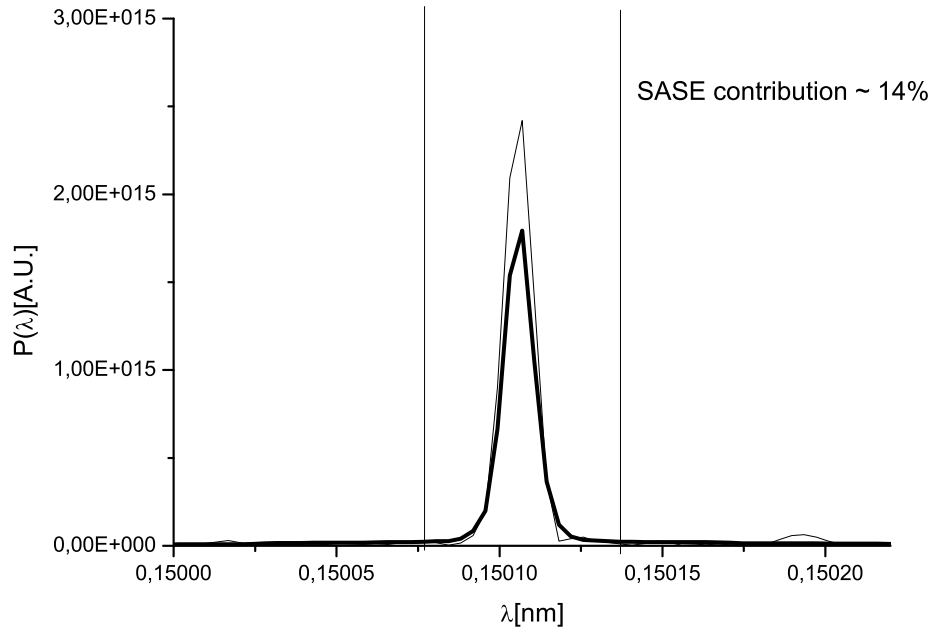


Fig. 15. Two-undulator configuration. Short pulse mode of operation. Average and typical single-shot output spectrum (respectively, thick and thin solid lines). An estimation of the SASE contribution can be done by evaluating the total power outside the spectral window shown with black straight lines and dividing it to the spectral power integrated over all the spectrum.

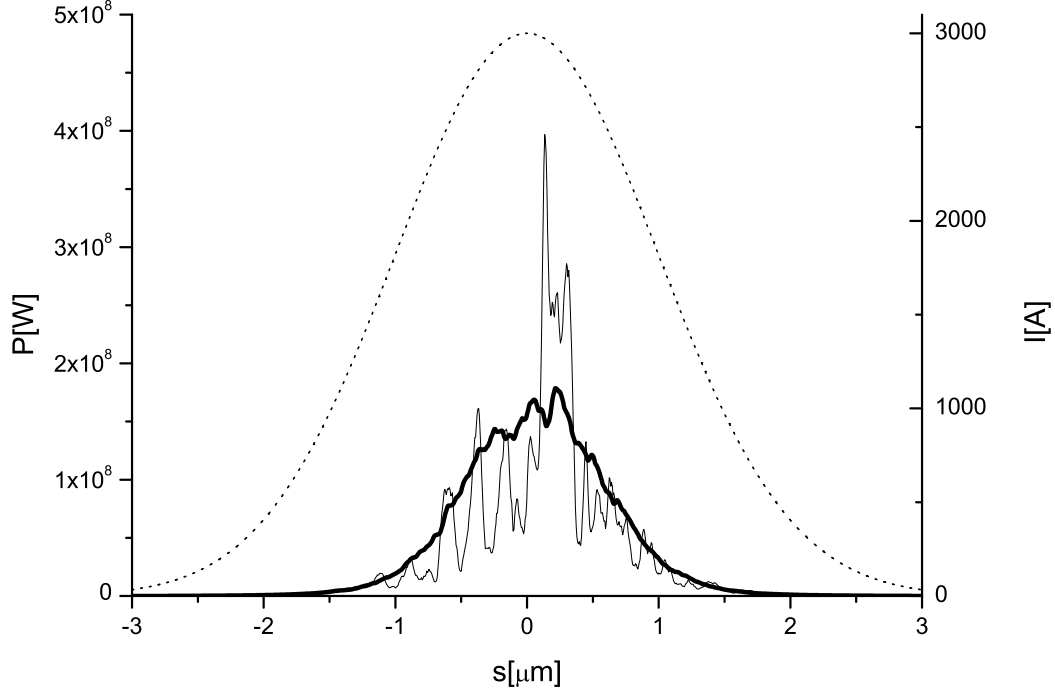


Fig. 16. Short pulse mode of operation, second monochromatization cascade. Input power at the second crystal, at the end of the second undulator, 7 cells long (42 m). The average input power is represented with a solid thick line. A typical shot is also shown with a solid thin line. The dashed line illustrates the corresponding distribution of the electron beam current.

4.2 Three-undulator configuration

As discussed before, the three-undulator configuration presents advantages related to the high contrast between seeded and SASE signal. With reference to Fig. 2 the second undulator is now shortened to 7 cells (corresponding to 42 m), and followed by a second seeding stage. The input power impinging on the second crystal is shown in Fig. 16.

As before, the effect of the filter is best shown by a comparison of the spectra before and after the filter, Fig. 17. A long, monochromatic tail in the power distribution on the left side of Fig. 18 constitutes the time-domain effect of the filtering procedure.

It is interesting to discuss here a paradox which arises when one compares the average spectrum before the filter (dotted line in Fig. 17) and the average spectrum after the filter in the first monochromatization cascade, Fig. 10. The bandstop filter effect is visible in the inset of the latter figure, but after amplification (dotted line in Fig. 17) it disappears, and no hole is visible in the spectrum anymore. This leads to an apparent contradiction, because the radiation pulse simply passes through a linear amplifier, and

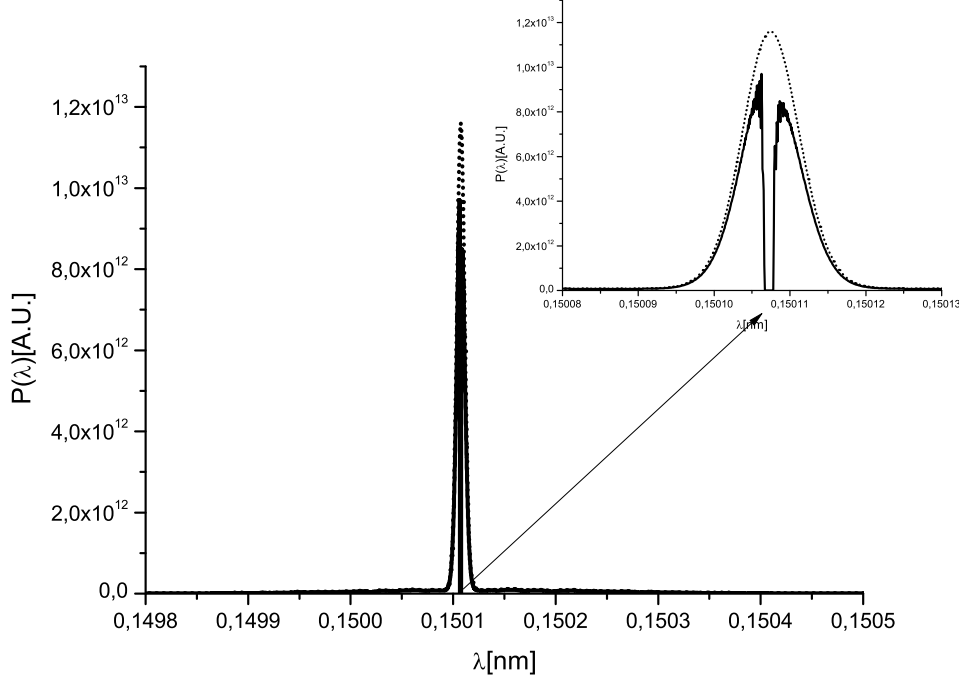


Fig. 17. Short pulse mode of operation, second monochromatization cascade. Average output spectrum after the second diamond crystal (solid thick line). The bandstop effect is clearly visible, and highlighted in the inset. For comparison, the average spectrum before the diamond crystal (dotted thick line) is also shown.

the bandstop effect should still be visible. The paradox is explained in terms of the windowing process. The monochromatic pulse at the exit of the first filter serves, in fact, as seed for the electron bunch, which is shorter than the monochromatic wake itself. The seeding field is effectively sampled only within the electron bunch. In other words, the temporal windowing process operated by the electron bunch is equivalent to a spectral measurement over a time equal to the bunch duration σ_e/c . The length of the monochromatic tail of the electric field (see Fig. 11) is related to the bandwidth of the crystal by inverse proportionality and is about $1/\Delta\omega_m$. When the two bandwidths are related by $\sigma_e/c \ll 1/\Delta\omega_m$, like in the short-pulse mode of operation, the windowing process in the time domain is equivalent to a convolution, in the frequency domain, of the seeding pulse and a window-like signal with bandwidth $c/\sigma_e \gg \Delta\omega_m$. It follows that the hole in the spectrum is not resolved or, in other words, that we are measuring the spectrum of the seed signal with an instrument (the electron bunch) which integrates over a temporal interval too short to obtain the proper resolution. The situation changes when the bunch length increases. This is equivalent to an increase in resolution in the spectral measurement, and can be seen in Fig. 31, which is the analogous of Fig. 17 for the long-pulse mode of operation. The electron bunch is not long enough to resolve the seed signal properly in the frequency

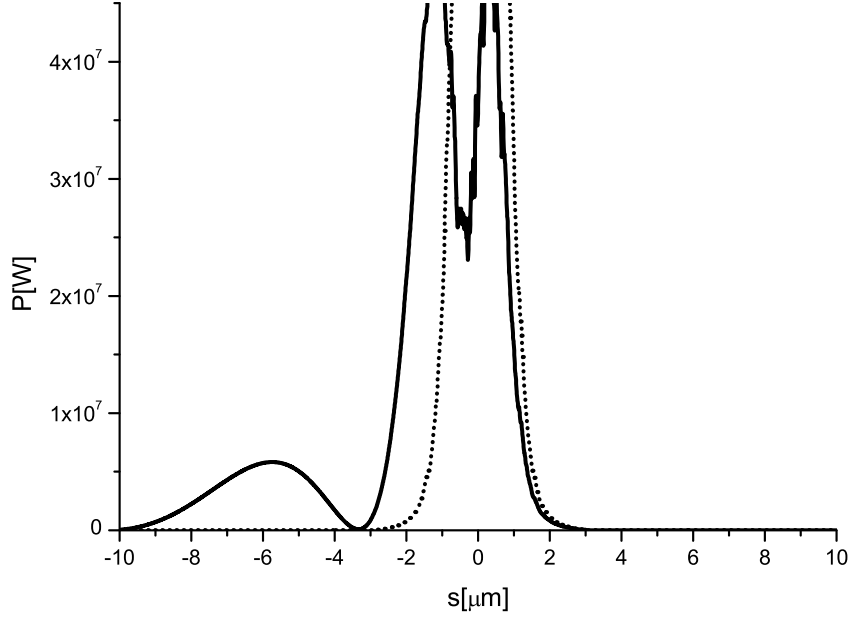


Fig. 18. Short pulse mode of operation, second monochromatization cascade. Power distribution before (dotted line) and after (solid line) transmission through the second crystal. The monochromatic tail due to the transmission through the bandstop filter is evident on the left of the figure.

domain, but the first filtering process is still visible in the dotted spectrum before the second filter, due to a better spectral resolution.

Following the second crystal, the radiation is used to seed once more the electron bunch. Radiation is collected at the exit of a third undulator. Fig. 19 and Fig. 20 respectively show the output power and spectrum for the three-undulator configuration, while in Fig. 21 and Fig. 22 we present, respectively, the rms deviation from the average and the average energy of the pulse as a function of the undulator length. Similarly as before, an estimation of the SASE contribution can be done by evaluating the total power outside the spectral window shown with black straight lines in Fig. 20, and dividing it by the spectral power integrated over all the spectrum yielding, as expected, a much smaller SASE contribution in the order of a percent.

5 Feasibility study for the long-bunch mode of operation

Let us now consider the case of long pulse mode of operation. The setups for the two-undulator configuration and for the three-undulator configuration

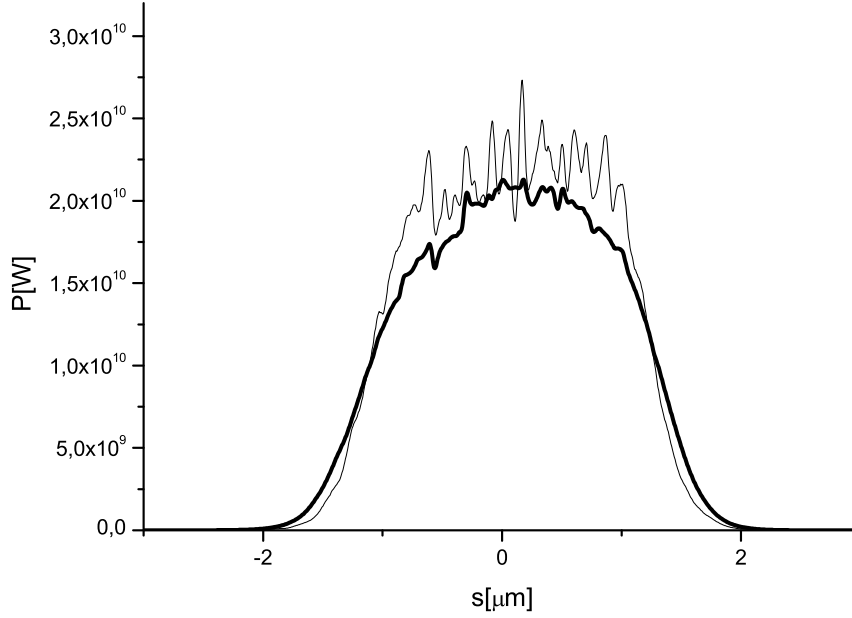


Fig. 19. Three-undulator configuration. Short pulse mode of operation. Average and typical single-shot output power (respectively, thick and thin solid lines).

are the same considered before, respectively in Fig. 6 and Fig. 2. As said above, for the long pulse mode of operations Table 1 is still valid, except for a ten times larger charge (0.25 nC) and a ten times longer rms bunch length (10 μm).

5.1 Two-undulator configuration

Similarly as before, we begin with the first monochromatization cascade. After the first seven cells (42 m) the electron bunch is sent through the weak chicane, while radiation is filtered through a single diamond crystal. We use the same crystal as before. The transmissivity function (modulus and phase) for the sigma-polarization component was already presented in Fig. 7, and Fig. 8. The profile of the radiation before the filter is shown in Fig. 23.

The effect is best shown by a comparison of the spectra before and after the filter, Fig. 24. A long, monochromatic tail in the power distribution can be clearly seen on the left side of Fig. 25. Compared to the previously discussed short pulse mode of operation, the seeding level is about an order of magnitude smaller.

Similarly as before, following the first crystal, we consider, first, a two-

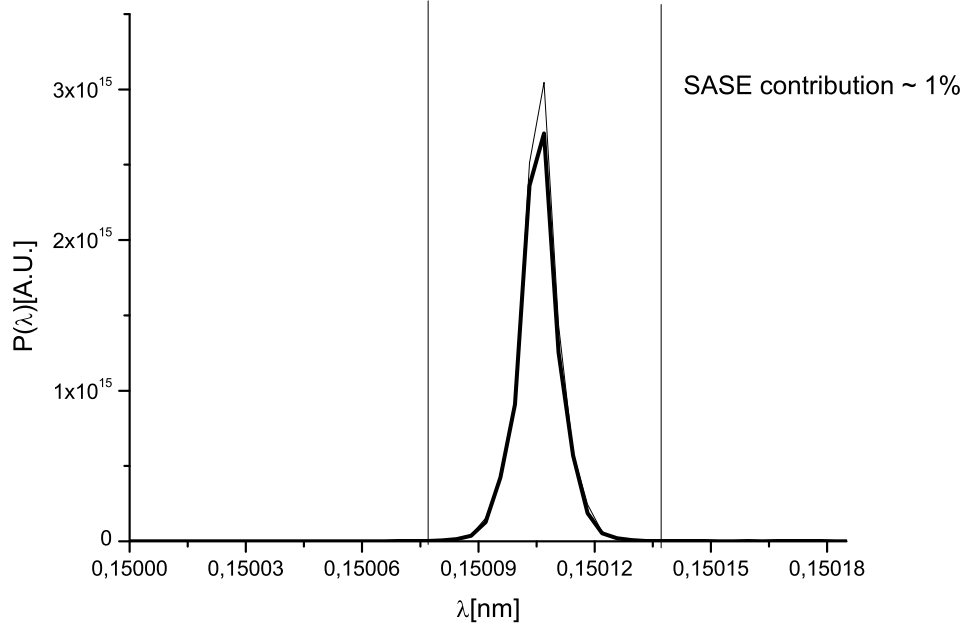


Fig. 20. Three-undulator configuration. Short pulse mode of operation. Average and typical single-shot output spectrum (respectively, thick and thin solid lines). An estimation of the SASE contribution can be done by evaluating the total power outside the spectral window shown with black straight lines and dividing it to the spectral power integrated over all the spectrum.

undulator configuration and, second, a three-undulator configuration. Although the average power of the seed signal after the first crystal amounts only to about 3 kW, the bunch length is now 10 times longer. Therefore, the contrast in spectrum can be comparable with the two-undulator configuration in the short pulse scheme.

Still with reference to Fig. 6, we optimized the length of the output undulator to obtain maximal spectral power. As before, the optimal length is found to be 12 cells. In Fig. 26 and Fig. 27 we show, respectively, the average energy of the pulse as a function of the undulator length, and the rms deviation from the average. Fig. 28 and Fig. 29 show, instead, the output power and spectrum. In the present case, an estimation of the SASE contribution yields an important SASE contribution in the order of 65%.

As before, we should remark that the two-undulator configuration may be particularly advantageous in cases when the total available undulator length is too short to enforce the three-undulator configuration. In this case, one may consider an increase in length of the first undulator in order to increase the contrast between seeded and SASE signal, at the cost of increasing the heat load.

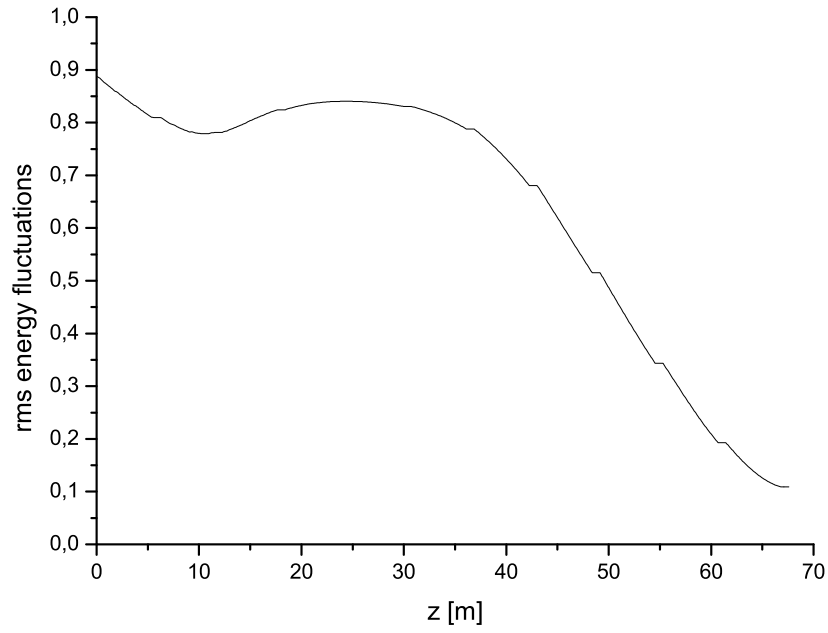


Fig. 21. Three-undulator configuration. Short pulse mode of operation. rms energy deviation from the average as a function of the third undulator length.

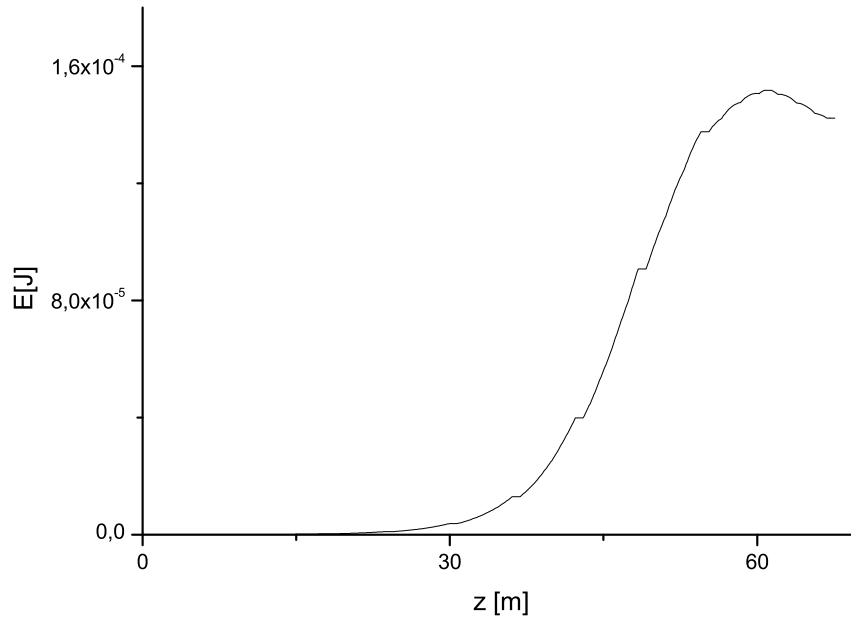


Fig. 22. Three-undulator configuration. Short pulse mode of operation. Average energy of the radiation pulse as a function of the third undulator length.

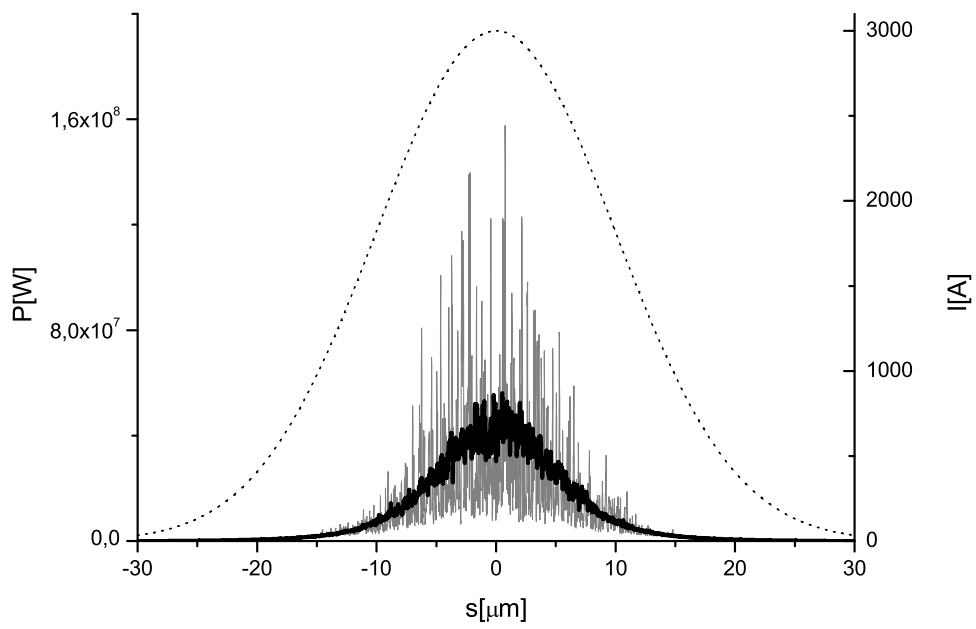


Fig. 23. Long pulse mode of operation. Input power at the crystal, at the end of the first undulator, 7 cells long (42 m). The average input power is represented with a solid thick line. A typical shot is also shown with a solid thin line. The dashed line illustrates the corresponding distribution of the electron beam current.

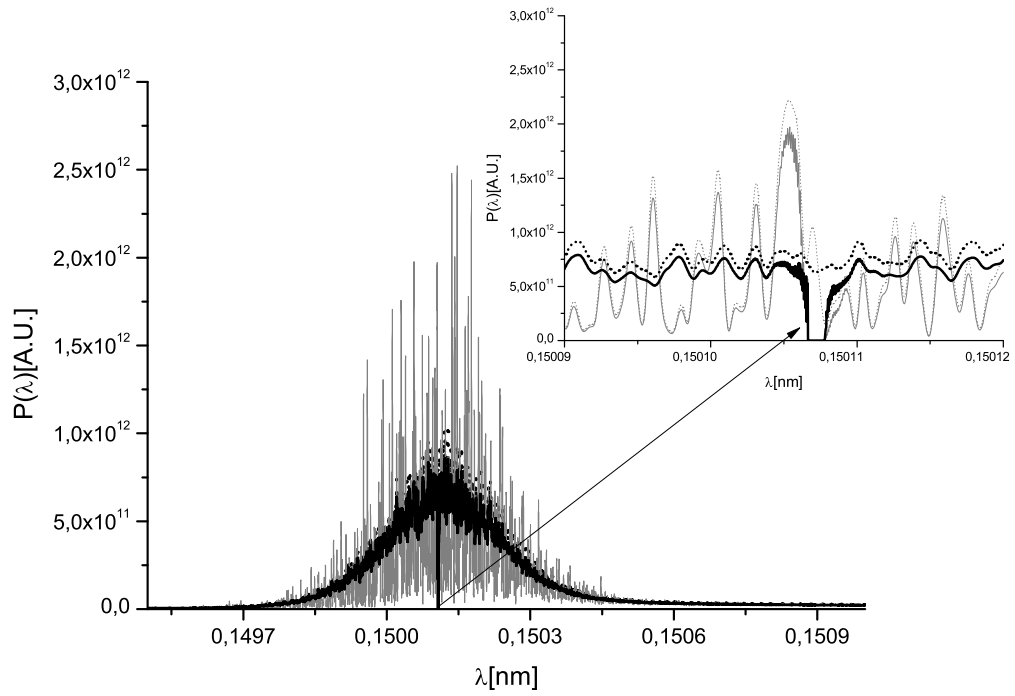


Fig. 24. Long pulse mode of operation. Average output spectrum after the diamond crystal and typical shot (solid thick line and solid thin line respectively). The bandstop effect is clearly visible, and highlighted in the inset. For comparison, the average spectrum before the diamond crystal and a typical shot (dotted thick line and dotted thin line respectively) is also shown.

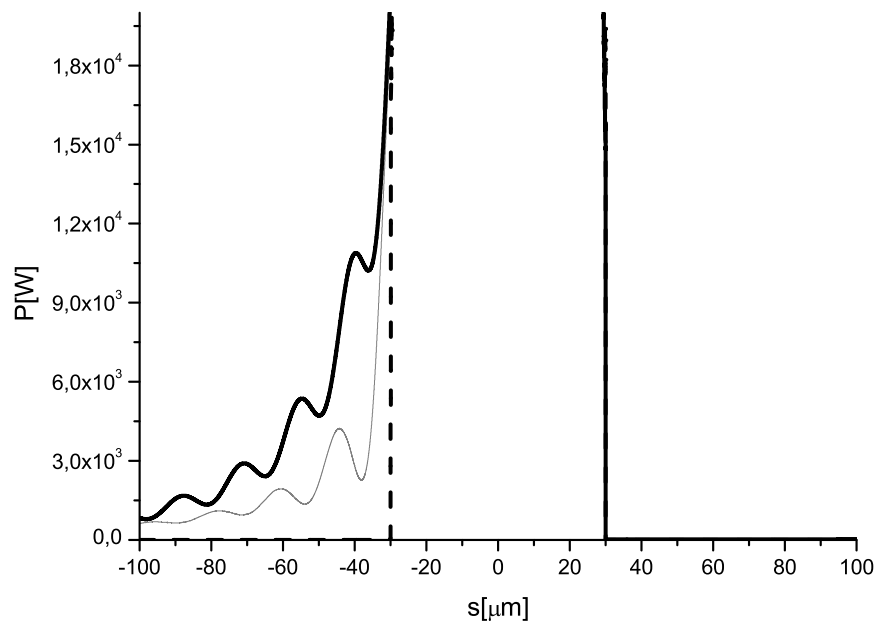


Fig. 25. Long pulse mode of operation. Power distribution before (dotted line) and after (solid line) transmission through the crystal. The monochromatic tail due to the transmission through the bandstop filter is evident on the left of the figure.

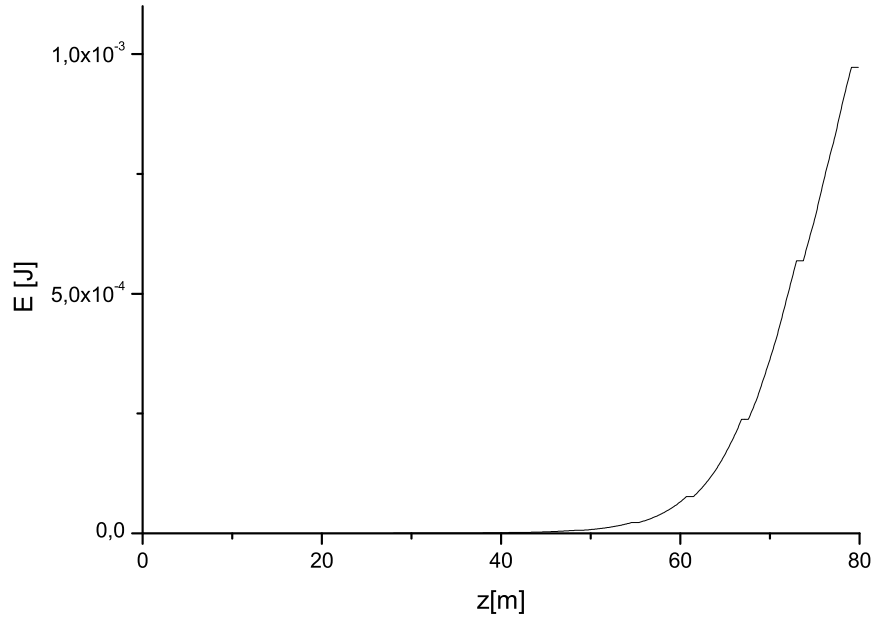


Fig. 26. Two-undulator configuration. Long pulse mode of operation. Average energy of the radiation pulse as a function of the second undulator length.

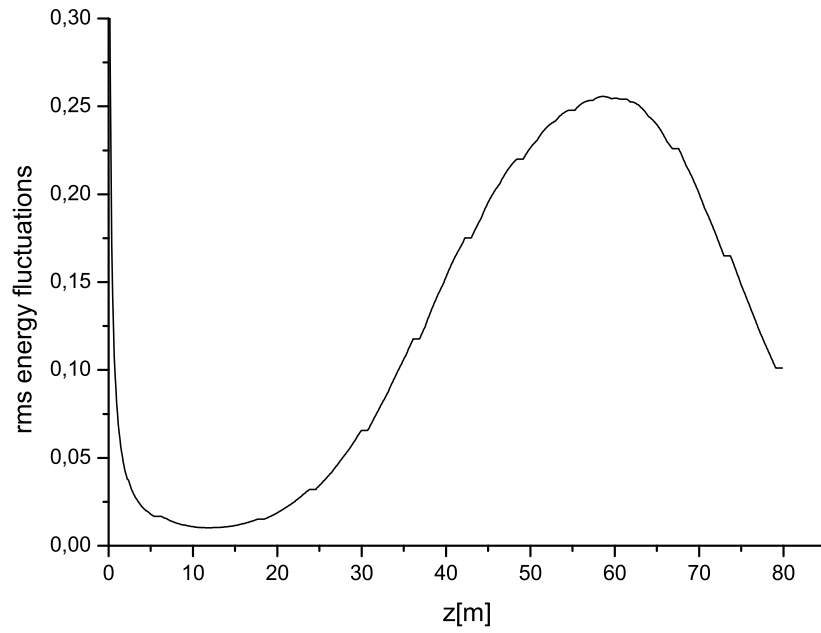


Fig. 27. Two-undulator configuration. Long pulse mode of operation. RMS pulse energy fluctuations along the second undulator.

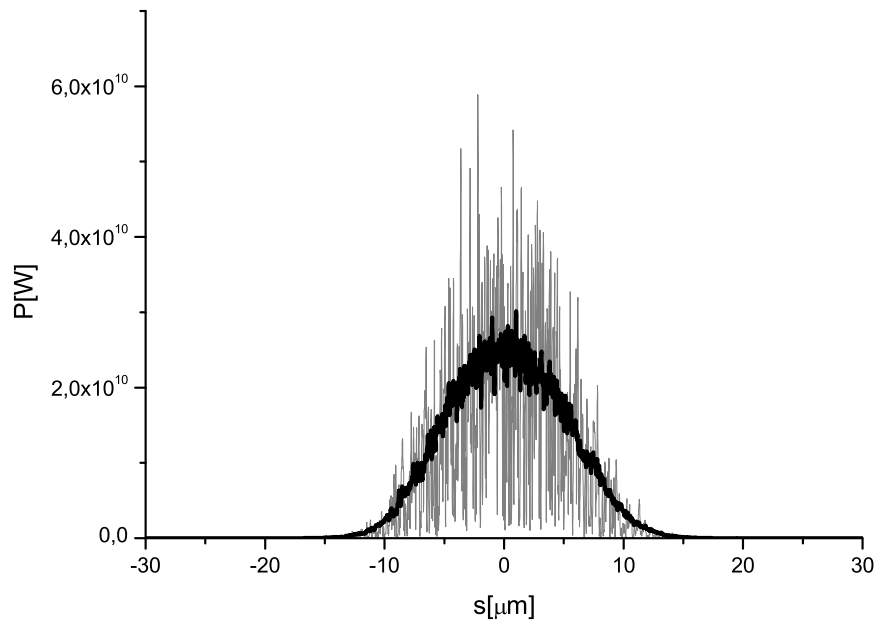


Fig. 28. Two-undulator configuration. Long pulse mode of operation. Average and typical single-shot output spectrum (respectively, thick and thin solid lines).

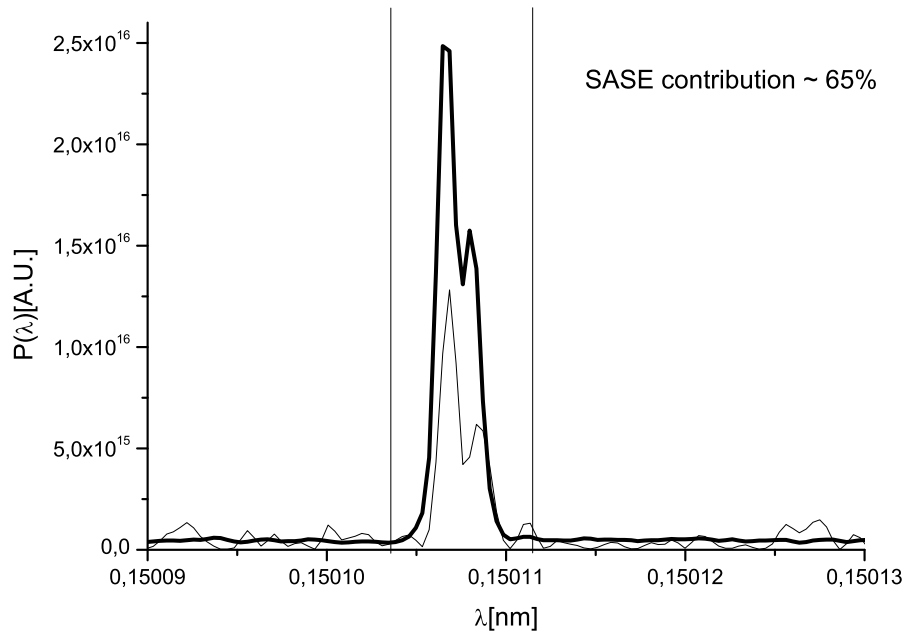


Fig. 29. Two-undulator configuration. Long pulse mode of operation. Average and typical single-shot output spectrum (respectively, thick and thin solid lines). An estimation of the SASE contribution can be done by evaluating the total power outside the spectral window shown with black straight lines and dividing it to the spectral power integrated over all the spectrum.

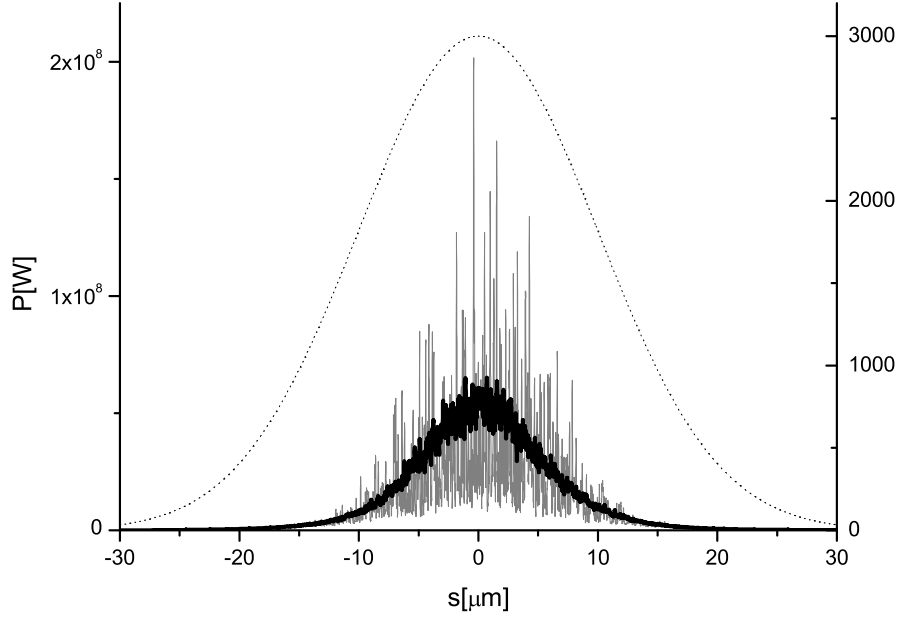


Fig. 30. Long pulse mode of operation, second monochromatization cascade. Input power at the second crystal, at the end of the second undulator, 7 cells long (42 m). The average input power is represented with a solid thick line. A typical shot is also shown with a solid thin line. The dashed line illustrates the corresponding distribution of the electron beam current.

5.2 Three-undulator configuration

As in the short pulse mode of operation, the three-undulator configuration presents advantages related to the high contrast between seeded and SASE signal. With reference to Fig. 2 the second undulator is now shortened to 7 cells (corresponding to 42 m), and followed by a second seeding stage. The input power impinging on the second crystal is shown in Fig. 30.

As before, the effect of the filter is best shown by a comparison of the spectra before and after the filter, Fig. 31. The long, monochromatic tail in the power distribution on the left side of Fig. 32 constitutes the time-domain effect of the filtering procedure.

Following the second crystal, the radiation is used to seed once more the electron bunch. Radiation is collected at the exit of a third undulator. Fig. 33 and Fig. 34 respectively show the output power and spectrum for the three-undulator configuration, while in Fig. 35 and Fig. 36 we present, respectively, the average energy of the pulse as a function of the undulator length, and the rms deviation from the average. The SASE contribution is strongly reduced

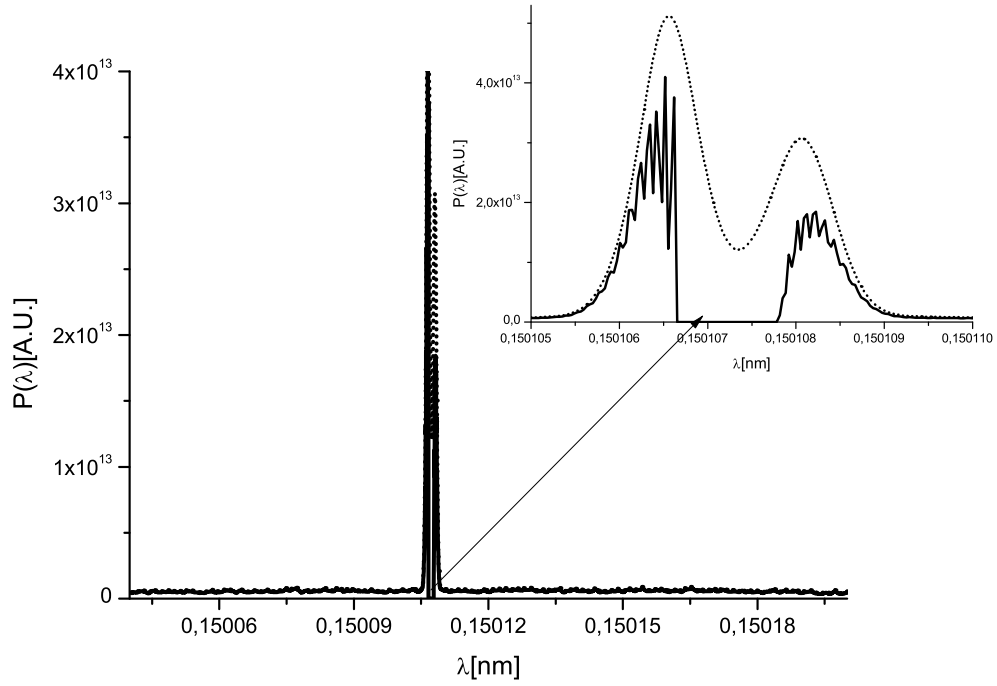


Fig. 31. Long pulse mode of operation, second monochromatization cascade. Average output spectrum after the second diamond crystal (solid thick line). The bandstop effect is clearly visible, and highlighted in the inset. For comparison, the average spectrum before the diamond crystal (dotted thick line) is also shown.

to a few percent.

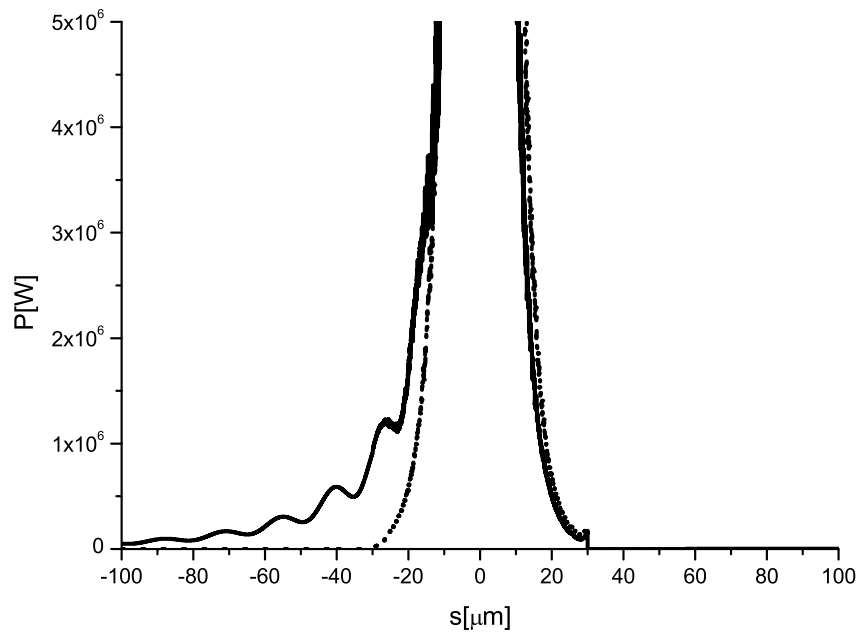


Fig. 32. Long pulse mode of operation, second monochromatization cascade. Power distribution before (dotted line) and after (solid line) transmission through the second crystal. The monochromatic tail due to the transmission through the bandstop filter is evident on the left of the figure.

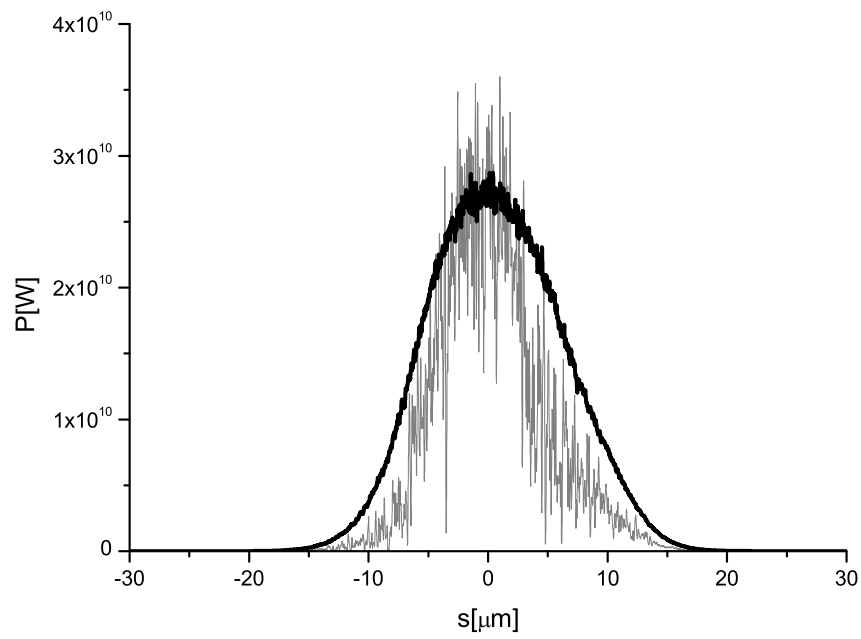


Fig. 33. Three-undulator configuration. Long pulse mode of operation. Average and typical single-shot output power (respectively, thick and thin solid lines).

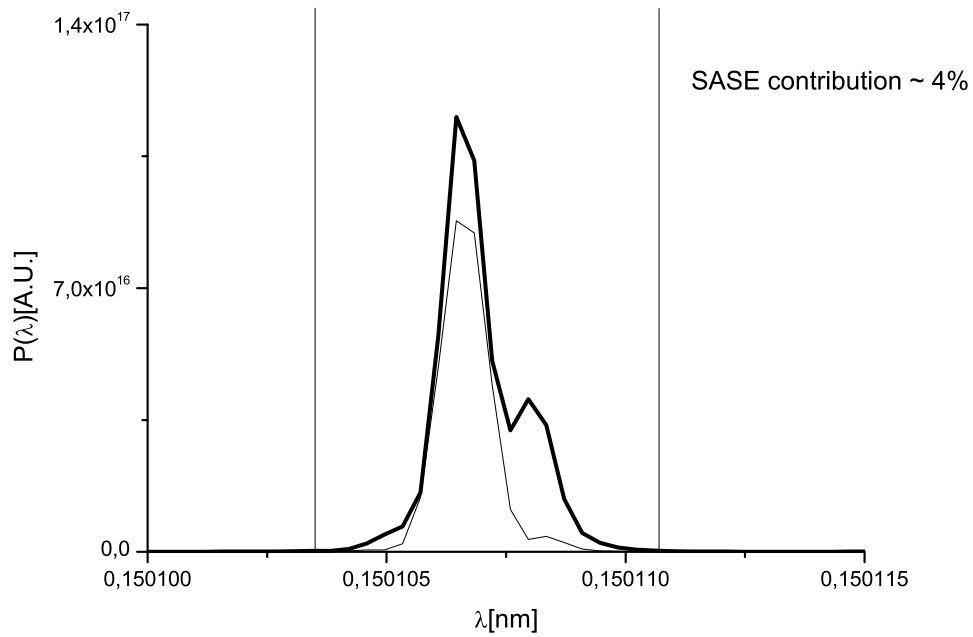


Fig. 34. Three-undulator configuration. Long pulse mode of operation. Average and typical single-shot output spectrum (respectively, thick and thin solid lines). An estimation of the SASE contribution can be done by evaluating the total power outside the spectral window shown with black straight lines and dividing it to the spectral power integrated over all the spectrum.

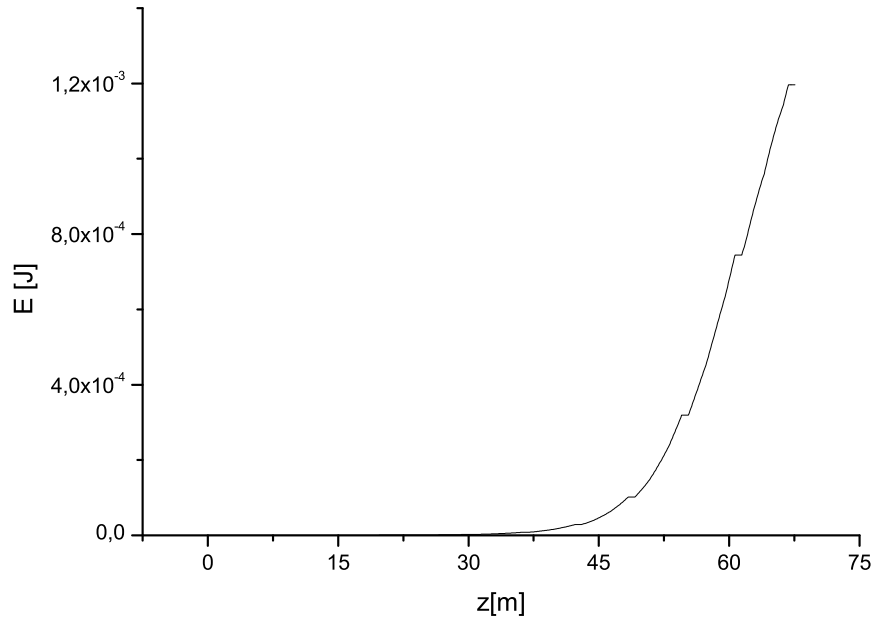


Fig. 35. Three-undulator configuration. Long pulse mode of operation. Average energy of the radiation pulse as a function of the third undulator length.

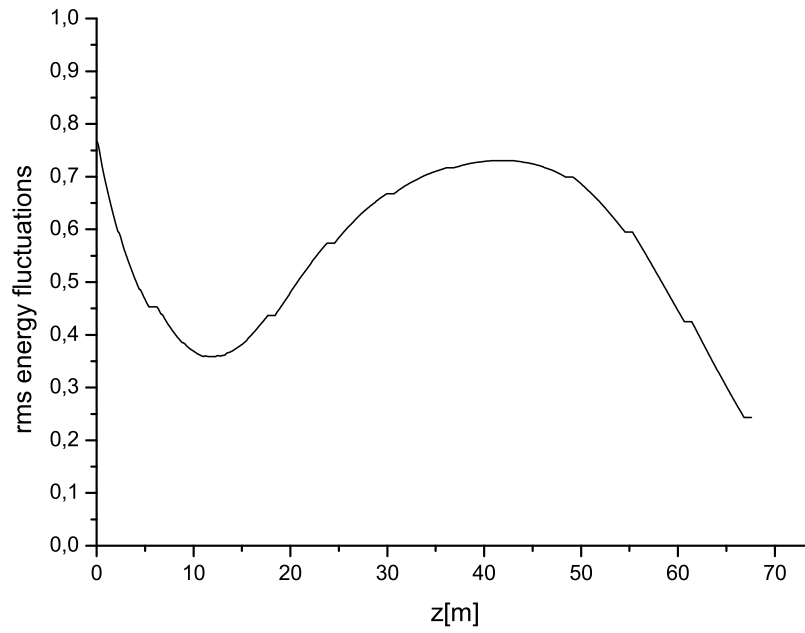


Fig. 36. Three-undulator configuration. Long pulse mode of operation. rms energy deviation from the average as a function of the third undulator length.

6 Conclusions

The fundamental problem of reducing the line width of SASE X-ray FELs is solved by implementing a self-seeding technique. In the present work, we described how to avoid the poor longitudinal coherence of hard X-ray SASE pulses. Quite surprisingly, monochromatization can be performed by an almost trivial setup composed of as few as two components: a weak chicane, and a single crystal. We have described techniques for reducing the line width of the output X-ray beam down to 10^{-5} , i.e. down to Fourier-Transform limit of the radiation pulse. We have shown how to achieve this monochromatization with small heat-loading of monochromators, which is crucial for the European XFEL. Many interesting applications can be found for these self-seeding techniques. However, in order keep this paper within a reasonable size, we did not discuss, here, possible applications of the proposed method, leading e.g. to further improvement of the XFEL performance. The proposed cascade self-seeding scheme based on the use of the wake monochromator is extremely compact and takes almost no cost and time to be implemented. It can be straightforwardly installed in the baseline undulator system of the European XFEL and is safe, in the sense that it guarantees the baseline mode of operation.

7 Acknowledgements

We are grateful to Massimo Altarelli, Reinhard Brinkmann, Serguei Molodtsov and Edgar Weckert for their support and their interest during the compilation of this work.

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