CONCEPTUAL STUDY OF A SELF-SEEDING SCHEME AT FLASH2

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Abstract

We present a conceptual study of a self-seeding installation at the new FEL beamline, FLASH2, at the free-electron laser at DESY, Hamburg. For self-seeding, light from a first set of undulators is filtered by a monochromator and thus acts as a seed for the gain process in the main undulator. This scheme has been tested at LCLS at SLAC with a diamond monochromator for hard X-rays and with a grating monochromator for soft X-rays covering energies between 700 and 1000 eV. For such a design to offer benefits at FLASH2, it must be modified to work with X-rays with wavelength of about 5 nm (248 eV) where the damage threshold of the monochromator in the setup and the divergence at longer wavelengths become an issue. An analysis of the potential performance and limitations of this setup is performed using GENESIS 1.3 and a method developed for the soft X-ray self-seeding experiment at the European XFEL.

With a total of 9 undulators in the first stage and 8 undulators after the monochromator, a pulse energy contrast ratio of 3.3 was simulated with an initial peak current of 2.5 kA.

INTRODUCTION

Starting the lasing process in Free-Electron Lasers (FELs) from noise limits the longitudinal coherence and shot-to-shot wavelength stability of the FEL radiation. To overcome the limitations of self amplified spontaneous emission (SASE) operation, the FEL process can be initiated by an external light field from either a tabletop laser or from an upstream FEL. When the seed light comes from an upstream FEL, the process is called self-seeding.

Self-seeding, originally proposed by [1], describes a seeding scheme in which the light from a first set of radiators is sent through a monochromator and used to seed a second set of radiators. It has been experimentally demonstrated at LCLS for hard X-rays [2] and soft X-rays with energies from 500-1000 eV [3, 4].

This is a study of a soft X-ray self-seeding design for FLASH2 [5]. An FEL energy of 248 eV was chosen because this is close to the high energy limit of operation. Our design is based on the one used at LCLS [4]. The simulation methods are adapted from the ones used for the European XFEL [6].

Our studies show that tolerances on the electron bunch are very tight due to the space constrains of FLASH2. To generate sufficient pulse energies in both, the first and the second undulator stage, the electron peak current has to be about 2.5 kA with an emittance of 1.5 mm mrad and a slice energy spread of 200 keV at an electron bunch energy of 1.1 GeV. These conditions are estimated through simulation alone and are not based on past performance at FLASH2. Achieving a slice energy spread of 200 keV with 2.5 kA peak current would be challenging. A larger energy spread would decrease the performance and self-seeding operation under the given space constraints would no longer be possible.

While losses in the monochromator are comparable to the LCLS and European XFEL designs, the divergence of the beam is larger due to the longer wavelength operation regime, leading to lower intensity and a best predicted pulse energy contrast between the seed and SASE background of 3.3.

Hardware Setup at FLASH2

FLASH2 is the second FEL beamline at FLASH, the Free-Eectron Laser at DESY in Hamburg. In this paper we describe a rearrangement of the 12 existing undulator modules as well as the addition of 7 further modules and a 3 m long chicane for self-seeding and study the performance given the space constrains.

Altogether there are 21 open spaces for the self-seeding undulators and chicane, 18 of which are filled in this design.

MONOCHROMATOR AND CHICANE

Monochromator Design

The monochromator shown in Fig. 1 consists of a variable line spacing (VLS) toroidal grating followed by a plane mirror (M1), a cylindrical mirror (M2) and another plane mirror (M3). Between the first and the second mirror, a slit is located: it allows for the selection of the transmitted bandwidth, stray light reduction and much easier alignment of the optics. The VLS grating focuses the dispersed wavelengths into lines at the slit position, while the grating sagittal curvature and M2 tangential curvature focus them in the middle of the first undulator module of the seeded undulator stage.

The monochromator parameters can be found in table 1 for a minimum of 200 eV (6.2 nm) and a maximum of 350 eV (3.5 nm) photons. The working point for the FEL simulations in this paper lies at 248 eV (5 nm).

Chicane Design

The chicane delay and the monochromator delay need to be approximately equal so that the longitudinal overlap with the radiation is preserved. The chicane additionally destroys the micro-bunching from the first undulator stage leaving a smeared out longitudinal charge density to be seeded in the main undulator.

The chicane as shown in Fig. 1 consists of 4 steering dipoles with 300 mm yoke length. The magnetic length of each magnet is given by 330 mm with a maximum possible magnetic field of 0.25 T. The FODO structure of FLASH2 limits the overall chicane length to about 3.2 m. The chicane parameters can be found in table 2 for the minimum and

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Table 1: Monochromator Parameters for Two Different Photon Energies of Photons (200 eV and 350 eV are the minimum and maximum values for the chicane. The working point for this paper will be 248 eV.)

Parameter	200 eV	350 eV
Grating		
position (z) [mm]	791	
line density [l/mm]	1000	
linear coeff [l/mm^2]	4.08	
quadratic coeff [l/mm^3]	0.0034	
tangential radius [m]	120	
sagittal radius [m]	0.200	
diffraction order	1	
incident angle [deg]	1	
exit angle [deg]	6.462	4.898
incident radiation peak intensity [GW/cm^2]	16	
M1		
position (z) [mm]	819.7	827.4
incident angle [deg]	3.731	2.949
Slit		
position (z) [mm]	2373	
width [µm]	3	
M2		
position (z) [mm]	2423	
incident angle [deg]	3	
tangential radius [m]	1.863	
M3		
position (z) [mm]	2459	
width [µm]	3	
transmission [%]	6.1	6.6

maximum photon energies of the monochromator. Since the delay of the monochromator changes with the wavelength of the photons, the magnetic fields of the chicane dipoles has to be adjusted to change its delay accordingly.

While traversing the chicane, the electrons are not only influenced by linear optics, but are also subject to coherent synchrotron radiation (CSR). To estimate the energy spread blow-up induced by CSR, simulations with the particle tracking code CSRtrack [7] have been done. The total energy spread of the electron bunch increases from about $\Delta\gamma = 0.44$ before the chicane to $\Delta\gamma = 0.74$ after the chicane.

Table 2: Chicane Parameters for Two Different Photon Energies of Photons (200 eV and 350 eV are the minimum and maximum values for the chicane. The working point for this paper will be 248 eV.)

Parameter	200 eV	350 eV
distance D_{12} [mm]	900	
distance D_{23} [mm]	200	
magnetic field [T]	0.2344	0.2207
deflection angle [deg]	1.10	1.03
R_{56} [mm]	0.808	0.717
horizontal offset h [mm]	23.0	21.7
horizontal offset after dipole h_I [mm]	2.88	2.71
timing difference Δt [ps]	1.469	1.302

In comparison to the 200 keV used in the simulation, an initial 500 keV keV slice energy spread based on measured performance at FLASH1 would increase the gain length in the first stage and a tenth undulator would be required to still achieve sufficient seed power for the second undulator stage. The CSR in the chicane would however increase this energy spread further. At an energy spread of about 1 MeV at the entrance of the second undulator stage, the saturation length of such an electron beam would exceed the space available at FLASH2.

Resolving Power

While the monochromator setup does employ an optional slit, there is a lower limit to the resolving power, R, the monochromator can operate with: the electron bunch itself acts as a slit since it is only in overlap with a specific fraction of the light pulse. This allows for coupling of a certain spectral range only and determines the amount of power coupling to the electrons. From this, an instrumental function for the monochromator and the second undulator stage describing the coupling factor of the seed radiation as a function of its wavelength can be calculated. To estimate this resolving power the method proposed in [6] has been followed.

The monochromator gives a horizontal offset to different wavelengths at the point of interaction with the electron bunch in the second undulator stage. The overlap of the light pulse and the electron bunch will therefore get worse with higher $\Delta\lambda$ and thus diminish the coupling of the light to the electrons.

The results of the Genesis 1.3 [8] simulations are shown in Fig. 2. The input coupling factor is given by the peak power of the FEL pulse after a few gain lengths and is normalized to the peak power at perfect overlap. The resolving power of the setup is then given by the FWHM of the shown curve $R = \frac{\lambda}{\Delta\lambda} = 17500$.

Figure 3 shows the spectrum of the first undulator stage with the window that will be cut out by the monochromator

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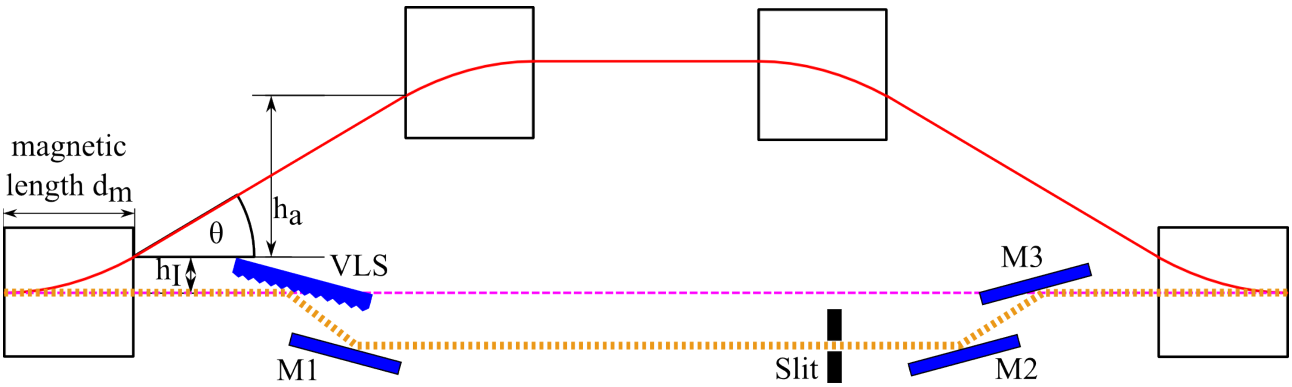

Figure 1: Drawing of the chicane between first and second undulator stage and monochromator. The red line shows the orbit of the electrons, while the yellow dotted line shows the path of the light pulse. Blue elements are optical element while the quadratic white boxes are the chicanes dipoles.

with the electron bunch acting as a slit. This window can be moved on the wavelength axis by rotating the M1 mirror.

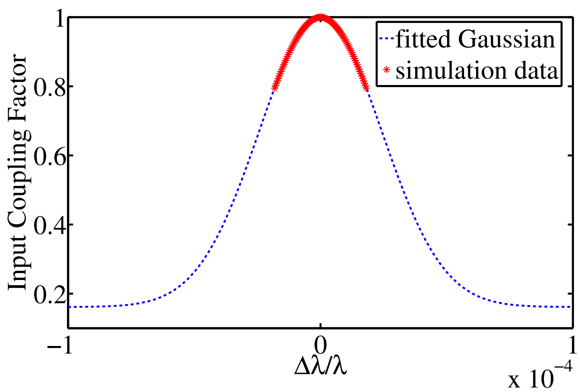

Figure 2: Input coupling factor as a function of wavelength difference of the incoming seed radiation. While the red crosses show Genesis 1.3 simulation results, the blue dashed line is the Gaussian Fit, giving the resolving power.

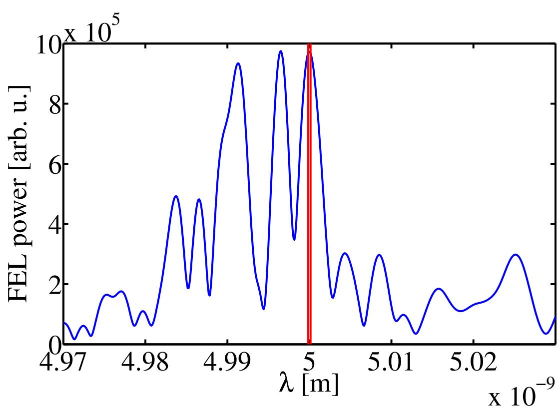

Figure 3: Spectral output of the first undulator stage. The blue lines show the fraction cut out by the resolving power of the electron bunch.

This resolving power is, however, a local property since $\frac{d\lambda}{dx}$ increases linearly with the z position along the undulator. The resolution is given after 2-3 gain lengths after which the seed radiation coupled to the electron bunch.

FEL SIMULATIONS

First Undulator Stage

The first undulator stage of the self-seeding setup has to deliver enough input power to successfully seed the second stage with the monochromator losses and resolving power taken into account. A Genesis 1.3 simulation for the SASE case at 5 nm for FLASH2 has given the properties of the FEL pulse after different numbers of FLASH2 undulator modules.

Table 3: Photon Pulse Properties After Different Number of Undulator Modules for the First Undulator Stage (divergence and beam size of the light pulse are given at the maximum power along the undulator axis)

Undulator Modules:	**7**	**8**	**9**
photon pulse energy [µJ]	0.282	1.020	3.939
divergence [mrad]	0.7	0.7	0.6
beam size (rms) [mm]	0.18	0.14	0.12
SASE bandwidth $(\Delta\lambda/\lambda)_{\mathrm{SASE}}$	1.75%	1.59%	1.46%
resolving power R_{m}	17500	17500	17500
photon pulse energy monochromator [pJ]	55	229	924

Table 3 shows the resulting photon pulse properties and the estimated results for the pulse after the monochromator. The photon pulse energy after the monochromator is estimated by

$$E_{\mathrm{in}}^{(2)} = \frac{T_{\mathrm{m}}}{R_{\mathrm{m}}(\Delta\lambda/\lambda)_{\mathrm{SASE}}} E_{\mathrm{out}}^{(1)}, \tag{1}$$

where $E_{\mathrm{in}}^{(2)}$ denotes the input pulse energy of the second undulator stage, $E_{\mathrm{out}}^{(1)}$ the output pulse energy of the first

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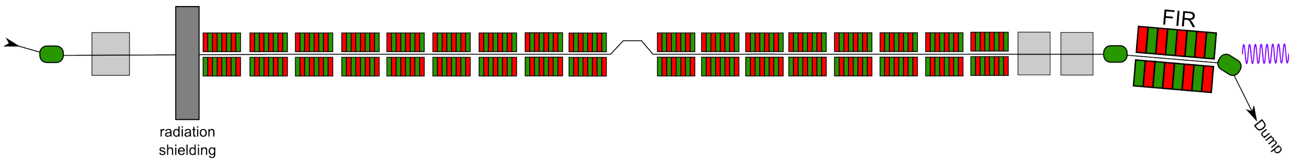

Figure 4: FLASH2 layout for a possible self-seeding scheme at 5 nm. The grey boxes show places where additional undulators could be installed if required. The last space was reserved for either a transverse deflecting structure or afterburner. The space before the radiator could be used for a seeding scheme.

undulator stage, T_m the transmission of the monochromator, R_m its resolving power.

From this we recommend a total of 9 undulators in front of the monochromator to have sufficient seed pulse energy of about 924 pJ with a pulse length of 129 fs and from this a peak power of about 6 kW for the second stage.

According to the simulations the laser beam on the grating will have a peak fluence of 12 µJ/cm^2, that is 4 orders of magnitude lower than the expected damage threshold of about 1J/cm^2 while repetition rate does not exceed 120 Hz [3].

Seeded Undulator Stage

The Genesis 1.3 simulations for the undulators after the monochromator employ Gaussian electron and seed pulses only. The properties of the electron beam are derived from the first stage and the chicane effects (such as CSR), the properties of the seed pulse are defined by the first stage and the above discussed influence of the monochromator. It is, however, not the same electron distribution, but a newly generated one that goes into this simulation. From the properties of the first undulator stage and the monochromator an input seed pulse energy of 924 pJ and a pulse length of 129 fs can be expected.

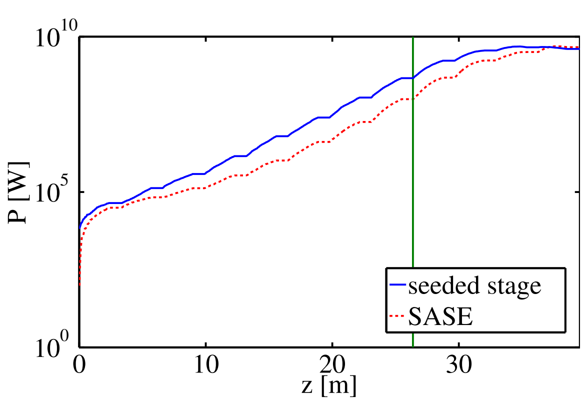

Figure 5: FEL gain curves for a 6 kW seeded electron bunch, compared to a SASE case. The green vertical line shows the end of the 4th FODO cell and with this the 8th undulator modules. The energy contrast ratio between the seeded light pulse to the SASE background is about 3.3.

Figure 5 shows FEL peak powers for a 6 kW seed compared to the SASE case. It can be seen that the seeded run reaches saturation after 9 undulators at about 30 m. To measure the performance of a self-seeding, experiment not only the peak power of the FEL light, but also the spectral brightness and contrast to the SASE case is important.

Figure 6 shows the spectral profiles of the FEL pulse after 8 undulator modules compared to the SASE case. The energy contrast of the seeded FEL pulses compared to SASE pulses is about 3.3 . When using 9 undulators for the second stage this contrast decreases by a factor of 2 which is why this study recommends 8 undulator modules for the second radiator stage with a final peak power of $P_{\mathrm{Peak}} \approx 0.5$ GW.

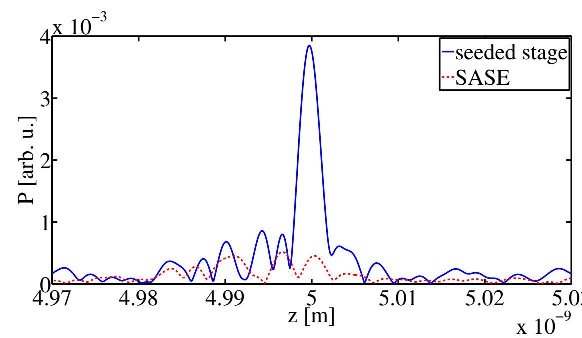

Figure 6: Spectral power profile of FEL pulses 8 undulators. The red line shows the SASE background and the blue line the seeded FEL pulse.

Its bandwidth is estimated by a Gaussian fit to be $(\Delta\lambda/\lambda)_{\mathrm{seeded}} \approx 7.5 \cdot 10^{-4}$. This is a factor of about 20 narrower than the SASE bandwidth. Given this bandwidth a transform limited pulse would have a length of $\Delta t \approx 9.1$ fs, while the FEL pulse from the simulation has a length of $\Delta t \approx 18.3$ fs and thus close to Fourier limited.

Figure 4 shows the proposed arrangement of undulators and the chicane for a possible self-seeding setup at 5 nm.

CONCLUSION

A possible self-seeding setup at the FLASH2 facility has to deal with tight space constraints and has thus to run at high peak currents of about 2.5 kA to be able to generate seeded FEL pulses close to saturation with a bandwidth about 20 times narrower than the SASE pulse.

While the calculations show a peak power of 6 kW after the monochromator, it might be very challenging to achieve this performance from both the monochromator and the first undulator stage, since this study has been taken out with ideal Gaussian bunches and pulses. Less power from the first stage would lead to a worse energy contrast and less

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peak power of the final FEL pulse. All calculations have to be redone with a full start-to-end simulation and based on experience at FLASH2 in order to determine the tolerances more accurately.

Additionally the monochromator needs to be further optimized to allow a lower resolving power and thus leading to more energy in a shorter light pulse with a reasonable divergence and focus point.

The present simulation shows that a self-seeding scheme at 5 nm would use 9 undulator modules in the first stage, a 3 meter chicane spanning only one undulator slot and 8 undulator modules for the second set of radiators. There are 21 available slots for hardware, 18 of which are used up in this design. To account for the possibility of poorer performance in this first undulator stage, an additional radiator would be recommended, leaving 2 open slots, one at the end for a TDS or afterburner, and one at the beginning for a compact external seeding concept.

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