STUDY OF A SILICON BASED XFELO FOR THE EUROPEAN XFEL

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Abstract

For the European XFEL in Hamburg three different SASE undulators whose radiation output have a high peak brilliance up to 5.4e33 photons/ $\left(\mathrm{s\,mm^2\,mrad^2\,0.1\%\,BW}\right)$ at wavelengths down to below 1e-10 m are planned. The radiation pulses are nearly fully coherent in transverse direction but have a poor longitudinal coherence of about 0.3 fs. Several schemes i.e. self seeding schemes were studied to get a better longitudinal coherence. In this paper an X-ray Free Electron Laser Oscillator whose radiation output is nearly fully coherent in all directions is presented. In contrast to previous schemes Silicon crystals in back reflection are used to form the cavity. The advantage of using Silicon is the availability of perfect crystals in almost every size and crystal geometry. However Silicon has a lower reflectivity and heat conduction than Diamond. To overcome the lower round trip reflectivity of a Silicon cavity a 15 m long undulator could be used to get a sufficiently large gain. To reduce the heat load an extremely asymmetric crystal geometry has to be used to enlarge the beam spot on the crystal.

INTRODUCTION

The beam parameters of European XFEL allow to operate high gain FELs. Sufficient high gain levels for multi pass approaches with significant shorter undulators can be reached. For an XFELO for the European XFEL the undulator length is assumed to be ca. 15 m long instead of the SASE undulators which need to be at least 60 m for wavelengths of 1.5 Å and even longer for two stage approaches [2]. The bandwidth of the radiation of an XFELO is more narrow than for SASE FELs ($\Delta\nu/\nu > 10^{-4}$) and will be in the order of $\Delta\nu/\nu \approx 10^{-6}$.

A cavity scheme to feed back the X-rays to the entrance of the undulator has been proposed for ERLs some years ago [5]. The cavity is based on BRAGG-deflecting crystals. Some studies have been done on cavities using Diamond crystals due to their high reflectivity and heat conduction [6, 7].

The disadvantage of using Diamond is the unavailability of large-size and defect-free crystals. Instead, Silicon crystals are available in almost every size and quality but with a lower peak reflectivity like Diamond. To compensate the lower reflectivity the undulator length has to be slightly longer. A second draw back of Silicon is the lower heat conduction and higher absorption [8]. Enlarging the beam spot by using an asymmetrical diffraction geometry

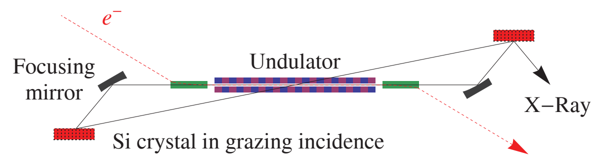

Figure 1: Schematic layout of a Silicon based cavity for an XFELO. The curved grazing incidence (black) mirrors match the undulator radiation back to the undulator entrance. To feed back the light to the undulator Silicon BRAGG deflection crystals (red) are used. The bending magnets (green) feed in the electron bunch (dashed red line) into the resonator.

to reduce the heat load could be a solution to compensate the lower heat conduction.

CAVITY LAYOUT

A Silicon based cavity for X-rays consists of two Silicon BRAGG deflection crystals and two focusing grazing incidence mirrors. In between are an undulator and two bending magnets to get the electrons into the cavity through the undulator and out of the cavity. In Fig. 1 a schematic setup of the resonator is depicted. A cavity using Silicon crystals in an extreme asymmetrical geometry with an angle of incidence α of about few mrad to the surface will enlarge the footprint on the crystal. Since the angle of incidence is close to zero and the BRAGG angle close to $\pi/2$ it will not be possible to build up an in wavelength tunable resonator like the 4-crystal-scheme [9]. For smaller angles of incidence surface errors will be larger because the luminous area gets larger and the surface error gets bigger. These surface errors may lead to wave front aberrations which reduce the FEL-gain. The use of four grazing incidence elements increases this effect. The asymmetrical diffraction geometry of the first BRAGG deflection crystal deforms the wave front which has to recombined by the second BRAGG deflection crystal. Differences of the surface and the orientation of the crystals lead to additional wave front errors.

For Diamond based cavities the out coupling will be realized by using a thin crystal to transmit a fraction of the circulating radiation out of the cavity. For Silicon based cavities one does not want to lose the advantage of a thick crystals which are easier to handle. There are two ideas of coupling out a fraction of light. The first one is to use the total reflection. Therefore the crystal has to detuned slightly from BRAGG angle. The second one is to use a 3-beam case for BRAGG reflection which would be more difficult to achieve.

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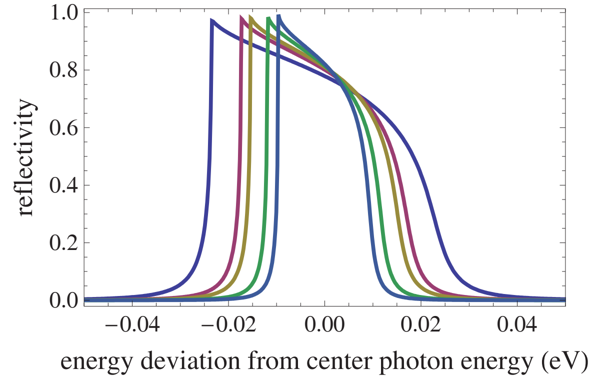

Figure 2: Reflectivity of Si crystals. Blue Si (444) at 7.91 keV. Magenta Si (800) at 9.13 keV. Yellow Si (660) at 9.86 keV. Green Si (664) at 10.71 keV. Light blue Si (1020) at 11.65

SIMULATION SETUP

Two different FEL simulation codes were used to study the radiation properties of an XFELO for the European XFEL. First GINGER a 2D simulation code and secondly the 3D code GENESIS with OPC were used [12, 13, 14]. GINGER was extended by the developer to read in a filter file which incorporates the characteristics of the BRAGG reflection. The used version is able to simulate wavelengths down to 1 Å and a resonator configuration of two curved mirrors in a certain distance. For the simulations a 15 m long undulator and a mirror distance of 30 m were assumed. The different filter characteristics are shown in Fig. 2.

With GENESIS and OPC (a surrounding framework) it is possible to simulate oscillators. For all presented results using GENESIS, it runs in steady state mode. The resonator which is defined by OPC has more degrees of freedom to set up. It also gives the possibility to insert multiple components or disturbances i.e. to include tilt alignment errors or phase masks to simulate wave front errors. For GENESIS simulations an undulator length 15 m, a distance from the undulator to the focusing mirrors is 7.5 m with a mirror curvature of 15 m were used. The BRAGG deflection crystals are placed 1.67 m behind the focusing mirrors. The total length of the cavity is about 66.66 m.

The round trip reflectivity in case of using GINGER is about 65 %-70 % and in case of GENESIS 73 %.

XFELO-SIMULATIONS

- In Fig 3(a) the radiation pulse energy against number of undulator passes is shown for five different photon energies (7.91 keV, 9.13 keV, 9.86 keV, 10.71 keV, 11.65 keV) using beam parameters listed in tab. 1. The corresponding reflectivity of the Silicon crystals is presented in Fig. 2. Apparently the gain decreases with photon energy. The stored energy decreases for shorter wavelengths. The pulse duration stays almost constant (Fig. 3(e)). The frequency width gets slightly smaller by increasing the photon energy from $\Delta\nu/\nu_0 \approx 2.6 \cdot 10^{-6}$ to $1.1 \cdot 10^{-6}$ (Fig. 3(i)).

Table 1: Beam Parameter used for FEL Simulations. E_B: Beam energy, σ_E: Rms beam energy error, Q: Charge, L: bunch length, ε_N: normalized slice emittance, I_P: Peak current.

Parameter		Beam energy	Wave length
E_B	GeV	8.0 – 18.0	14.0
σ_E	MeV	1.2	0.45
Q	nC	0.5	1.0
L_{fwhm}	fs	235	75
ε_N	µm	0.65	1.0
I_P	kA	2.0	4.9

		Bunch length					
E_B	GeV	14.0					
σ_E	MeV	0.44					
Q	nC	0.5					
L_{rms}	fs	0.05	0.08	0.1	0.2	0.3	0.4
ε_N	µm	0.7	0.65	0.65	0.6	0.6	0.55
I_P	kA	4.0	2.5	2.0	1.0	0.7	0.5

- In Fig. 3(b) the dependency on the gain with the electron beam energy is shown. The electron energy was changed from 8 GeV to 18 GeV. Except the K-parameter the simulation parameters stay constantly (tab.1). The FEL-gain increases for higher energies so that the number of round trips until saturation decreases. The radiation pulse duration ($t_{\text{light, FWHM}} \approx$ 160 fs) and the bandwidth ($\Delta\nu/\nu_0 \approx 1.4 \cdot 10^{-6}$) do not change with energy (Fig. 3(f), 3(j)). The peak brilliance increases with energy by a factor of 100. If 10 % of the stored energy is coupled out the peak brilliance will be in the order of $PB = 7.5 \cdot 10^{34}$ photons/ $\left(\text{s}\,\text{mm}^2\,\text{mrad}^2\,0.1\%\,\text{BW}\right)$.
- The bunch length dependency of the amplification process is displayed in Fig. 3(c). The rms bunch length was changed from 50 fs to 400 fs. The charge was kept constant so that the current decreases correspondingly. Bunches longer than 400 fs have a too small gain to get a net amplification since the undulator length was too short and the round trip losses were too high. With increasing the bunch length the radiation pulse length gets longer (95 fs-370 fs). Since the pulses are nearly FOURIER-transform limited the frequency width decreases. This has been already reported in [9]. The stored energy and the frequency width ($\Delta E/E_{Ph} \approx 2.3 \cdot 10^{-6} - 0.6 \cdot 10^{-6}$) decrease for longer bunch lengths and the peak brilliance changes from $PB = 6.8 \cdot 10^{34}$ to $2.0 \cdot 10^{34}$ photons/ $\left(\text{s}\,\text{mm}^2\,\text{mrad}^2\,0.1\%\,\text{BW}\right)$ for 10 % outcoupling.
- The dependency of tilt alignment errors of mirrors in the cavity is shown in Fig. 3(d). The tilt is kept con-

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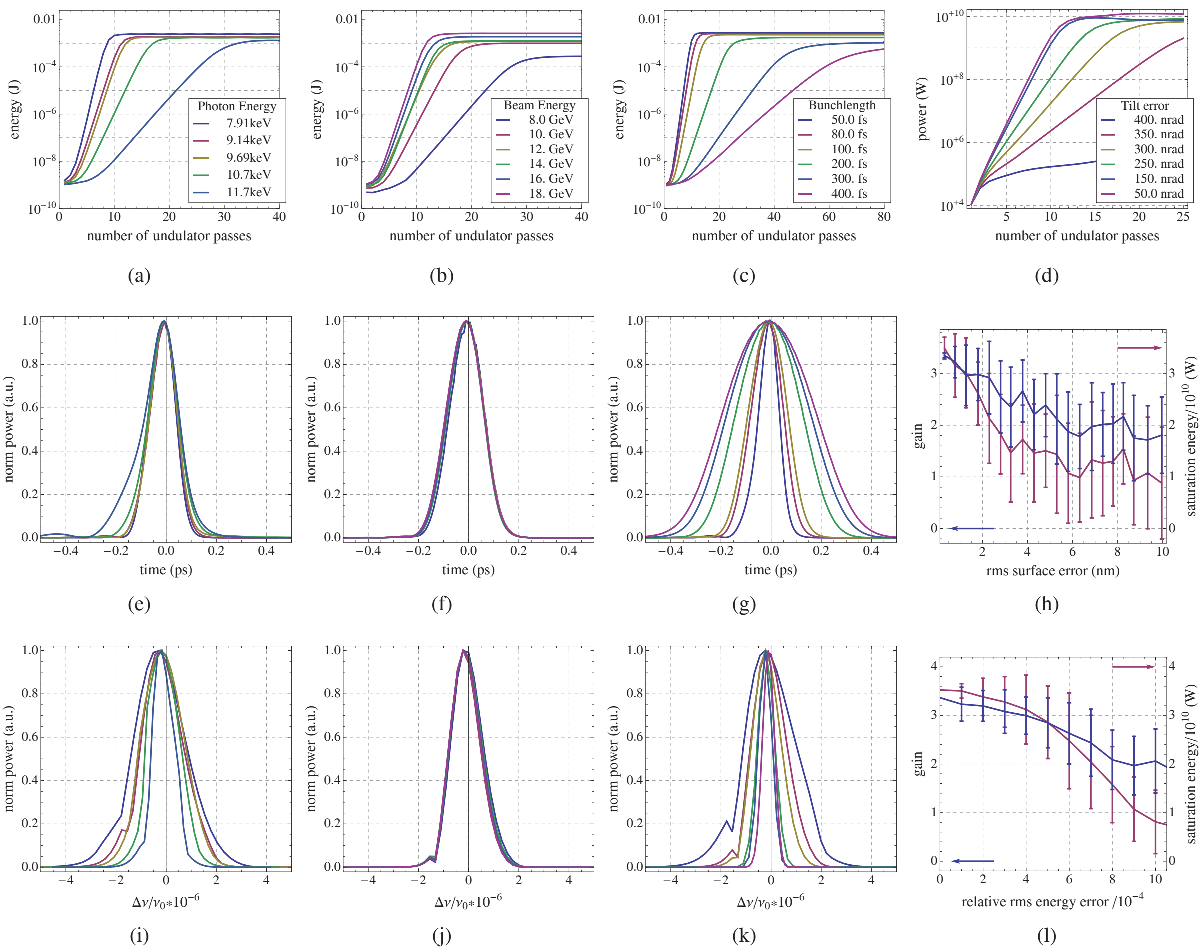

Figure 3: Some results of the simulation of an XFELO for the European XFEL. 3(a) Stored energy after the undulator passage for different wavelengths using silicon crystals as filter. 3(b) Stored energy after the undulator passage for different electron bunch energies using a Si (800) crystal. 3(c) Stored energy after the undulator passage for different electron bunch length using a Si (800) crystal. 3(d) Peak power of the radiation pulse for different mirror missalignment tilts. 3(e) Radiation pulse lengths for different wavelengths. 3(f) Radiation pulse lengths for different electron bunch energies. 3(g) Radiation pulse lengths for different electron bunch lengths. 3(h) Gain and saturation energy change against rms surface error. 3(i) Frequency widths for different wavelengths. 3(j) Frequency widths for different electron bunch energies. 3(k) Frequency widths for different electron bunch lengths. 3(l) Gain and saturation energy change against rms energy error of the electron bunch.

stant and is added on the first focusing mirror. The tilt was chosen from $\delta\alpha = 50$ nrad to $\delta\alpha = 400$ nrad in eight steps. Tilt errors smaller than 150 nrad have no big influence on the gain. As expected the gain decreases for larger tilts since the overlap between electron beam and photon field gets worse. For tilt alignment errors larger than 150 nrad the influence on the gain is strong. For even larger tilt errors no net gain was achieved. This agrees with the considerations which were done in [11].

- To simulate mirror surface errors a phase mask was created which modifies the radiation field. The path length differences are calculated as shown in [10]. A random path in 2D simulated the surface height errors. 420 different phase masks were created and sorted by the rms height errors. In Fig. 3(h) the result for surface height errors between $0 - 10$ nm is shown. Each point corresponds to the mean between $n <$ rms surface error $\leq n + 1$ with $n = 0, 1..10$ nm. An increasing surface height error leads to a reduction of the FEL gain and the stored energy. When a 2 nm rms surface height error is added the gain decreases ca. 10 %.

- The effect of an energy error of the electron bunch was simulated by changing the electron energy from round trip to round trip randomly in a certain range. For each range 100 runs were done. In Fig. 3(l) ten different error ranges are shown from $\delta E/E_0 = 10^{-4} - 10^{-3}$ in steps of 10^{-4}. An increasing energy error reduces the gain and the stored energy of the XFELO. In case

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of the European XFEL the relative energy deviation bunch to bunch will be in the order of $\Delta E/E_0 = 10^{-4}$. The change of the gain and saturation energy will not be significant.

HEAT LOAD SIMULATIONS

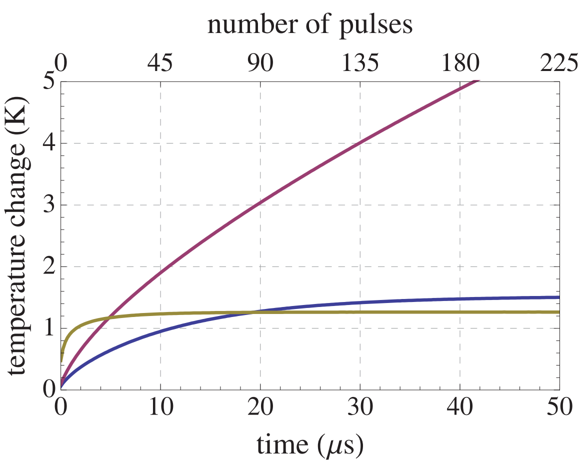

Figure 4: Heat load simulation for a Silicon crystal at 120 K for normal (magenta, temperature divided by 100) and grazing incidence (yellow) and Diamond at 100 K (blue) for 10 µJ absorbed pulse energy.

In Fig. 4 the crystal temperature is depicted for three different cases just before the energy is absorbed. For simulations a cylinder symmetrical 2D code written in IDL was used. The absorbed pulse energy was 10 µJ. The pulses were spaced by 222 ns and illuminate a 200 µm large spot. In case of grazing incidence the footprint of the beam was 100 times larger.

As expected the temperature rise for a Silicon crystal in normal incidence at an initial temperature of 120 K gets too large for operating an XFELO (The depicted temperature is divided by 100). In case of Diamond crystals the temperature is after 50 pulses 1.2 K above the initial temperature staying constantly. The corresponding energy shift of the rocking curve due to thermal expansion is $\Delta \mathrm{E}/\mathrm{E}_{Ph} = 1.1 \cdot 10^{-7}$ which is about 10 % of the energy width of the reflection. For the Silicon crystals in grazing incidence the temperature change after 300 pulses is 1.51 K and stays almost constant. The expansion coefficient of Silicon has a zero crossing at T $\approx$ 122. K so that the relative energy shift of the rocking curve is $\Delta \mathrm{E}/\mathrm{E}_{Ph} = 2.7 \cdot 10^{-8}$.

CONCLUSION AND OUTLOOK

In this paper a Silicon based XFELO for the European XFEL was introduced. Some gain studies have been done which show that it might be feasible to build up a Silicon based cavity.

The FEL simulations show that sufficient gain can be achieved by using a 15 m long undulator generating wavelengths between 1.5 Å and 1 Å. The XFELO can be operated for different electron beam energies hence the saturation energies for the X-ray pulse decreases for smaller bunch energies. This might be useful to reduce the heat load. Longer bunch lengths lead to smaller radiation bandwidths. Also the gain and the stored energy reduce. For a 15 m long undulator and bunch lengths longer than 400 fs rms the FEL-gain was too low to achieve a net gain.

Some errors which will occur have been studied using GENESIS in steady state mode. Mirror surface errors reduce the gain and lead to a reduction of the stored energy. Mirror tilt misalignments do not have a big influence up to 150 nrad. For larger tilts the gain decreases rapidly. Errors in the electron bunch energy lead to a reduction of the gain and the stored energy of the radiation. Expected bunch to bunch energy deviations for the European XFEL in the order of 10^{-4} do not influence the gain and stored energy significantly.

The simulations for the heat load on crystals show for a 100 times larger footprint on the Silicon crystal the energy shift due to the absorbed energy of the X-ray pulses seems to be manageable. An experimental setup is under construction to probe the X-ray characteristics of the BRAGG deflecting crystal using synchrotron radiation while the crystal is heated up using a laser source with a wavelength such that the absorption depth similar to the extinction depth of the BRAGG deflection.

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