X-RAY MONOCHROMATORS FOR SELF-SEEDING XFELs IN THE PHOTON ENERGY RANGE STARTING FROM 1.5 keV

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Abstract

Self-seeding of FELs with photon energies below 1 keV can be performed using grating monochromators [1]. Forward Bragg diffraction (FBD) monochromators [2] were instrumental for achieving self-seeding in hard x-ray FELs in the photon energy range from 5 to 10 keV [3]. Large photo-absorption in the monochromator crystal at lower photon energies makes extension into lower photon energy range difficult. Here an alternative scheme of x-ray monochromatization is introduced which may enable self-seeding in a yet inaccessible spectral range starting from 1.5 keV, and thus to bridge the gap between the soft and hard x-ray self-seeding.

The new scheme uses grazing-incidence Bragg diffraction under specular reflection conditions [4]. Specular reflection mitigates the problem of photo-absorption, as in this case the FBD radiation is reflected from a very thin crystal surface layer. Application of quartz (SiO_2) instead of diamond crystals, makes feasible Bragg diffraction and therefore monochromatization of x-rays starting from 1.457 keV.

INTRODUCTION

A new scheme of x-ray monochromatization is proposed here, which may enable self-seeding in a yet inaccessible spectral range starting from 1.5 keV, and thus to bridge the existing gap between the soft and hard x-ray self-seeding. The scheme uses grazing-incidence Bragg diffraction under specular reflection conditions [4], as shown in Figure 1.

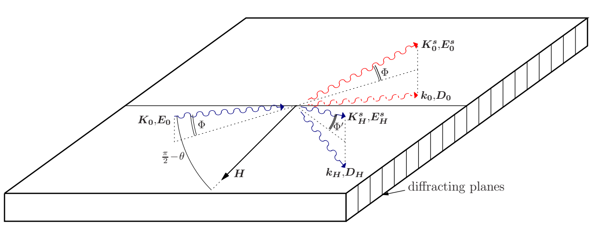

Figure 1: Schematic of grazing incidence x-ray Bragg diffraction in non-coplanar geometry under specular reflection conditions [4].

X-RAY DIFFRACTION UNDER SPECULAR REFLECTION CONDITIONS

Diffracting atomic crystal planes are perpendicular to the crystal surface. Incident x-rays with the wave-vector $\boldsymbol{K}_0$ are at a very small glancing angle of incidence Φ to the crystal surface, and at a Bragg angle θ to the diffracting atomic crystal planes ($\pi/ - \theta$ angle with diffraction vector $\boldsymbol{H}$). Under theses conditions, the Bragg diffracted x-rays propagate at a very small glancing angle of reflection to the crystal surface Φ'. $\boldsymbol{K}^s_H$, E^s_H are the wave-vector and the amplitude of the specularly reflected Bragg diffracted beam. Another Bragg diffracted component propagates inside the crystal with the wave-vector $\boldsymbol{k}_H$, and amplitude D_H. Similarly, there are two components of x-rays associated with forward Bragg diffraction (FBD). First, there is an in-crystal component with wave-vector $\boldsymbol{k}_0$ D_0. Second, $\boldsymbol{K}^s_0$, E^s_0 are the in-vacuum wave-vector and the amplitude of the specularly reflected forward Bragg diffracted beam (S-FBD), with the specular reflection angle Φ. Dinamical theory of Bragg diffraction in such scattering geometry has been developed by Afanasev-Melkonyan (1983). For the x-ray monochromator application we will be interested in the S-FBD beam E^s_0.

Specular reflection mitigates the problem of photo-absorption, as in this case the FBD radiation is reflected from a very thin crystal surface layer. Application of quartz (SiO_2) instead of diamond crystals, makes feasible Bragg diffraction and therefore monochromatization of x-rays starting from $\hbar\omega_H = 1.457$ keV, the photon energy for backscattering from the atomic planes with diffraction vector $\boldsymbol{H} = (10\bar{1}0)$. The nominal energy $\hbar\omega_0$ of photons involved in Bragg diffraction is defined as usually by Bragg's angle θ through Bragg's law: $\hbar\omega_0 = \hbar\omega_H / \sin\theta$.

SELF-SEEDING SCHEME

The x-ray FEL self-seeding scheme is shown in Figure 2. X-rays from the first half of the magnetic undulator system

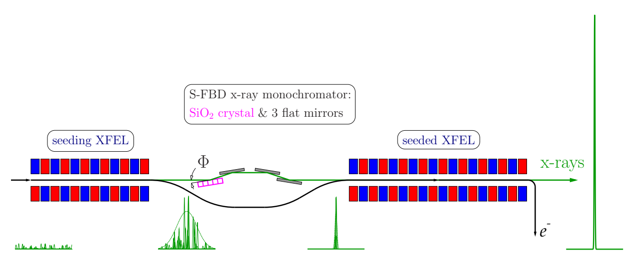

Figure 2: X-ray FEL self-seeding scheme with the S-FBD x-ray monochromator.

(seeding XFEL) are used to seed the electron bunch in the second half (seeded XFEL) via an x-ray monochromator consisting of a SiO_2 crystal and three flat grazing incidence mirrors, used to correct the trajectory of photons. The monochromator produces a delayed monochromatic seed through grazing incidence forward Bragg diffraction under specular reflection (S-FBD) conditions, with a small specular reflection angle $\Phi \lesssim 25$ mrad, see Fig. 1 for details. The

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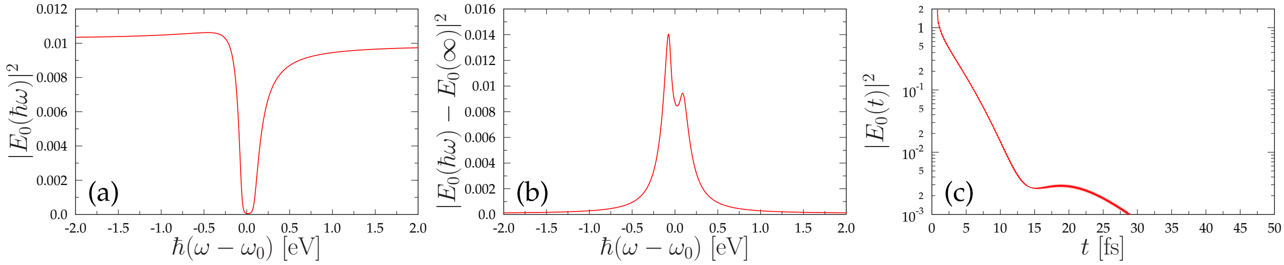

Figure 3: Forward Bragg diffraction (FBD) of 1.46-keV x-rays from a 10-μm SiO_2 crystal, the $(10\bar{1}0)$ Bragg reflection: (a) spectral dependence of x-ray transmissivity $|E_0(\hbar\omega)|^2$; (b) spectral dependence of forward Bragg diffraction $|E_0(\hbar\omega) - E_0(\infty)|^2$; (c) time dependence $|E_0(t)|^2$ of FBD. FBD is more than an order of magnitude weaker than the S-FBD signal, see Fig. 4(c), because of the strong photo-absorption in SiO_2.

small specular reflection angle Φ and a small spatial off-set of the mirrors $H \simeq 0.2$ mm ensures almost forward Bragg scattering with a small additional delay $\tau = 2\Phi H/c \simeq 30$ fs, due to a slightly detoured flight-path via the SiO_2 crystal and flat mirrors, assuming $\Phi = 22$ mrad.

S-FBD MONOCHROMATOR PERFORMANCE

Performance of the S-FBD monochromator is demonstrated in Fig. 4 by spectral and time dependencies of forward Bragg diffraction under specular reflection conditions (S-FBD) in SiO_2 for x-rays with photon energies $\hbar\omega$ in the vicinity of $\hbar\omega_0 = 1.46$ keV, the nominal energy of the $(10\bar{1}0)$ Bragg diffraction at $\theta = 86.14°$.

Spectral dependencies of S-FBD reflectivity for different glancing angles of incidence Φ, in the vicinity of photon energy $\hbar\omega_0 = 1.46$ keV, are shown in Fig. 4(a). At large deviations of photon energies from $\hbar\omega_0$ the reflectivity is flat, and corresponds to pure grazing incidence specular reflectivity with close to zero Bragg diffraction contribution. They correlate with the data for the angular dependence of the specular reflectivity of 1.46 keV photons from SiO_2 at grazing incidence angle Φ, shown in Fig. 4(d).

Spectral dependencies of the delayed part of S-FBD, with a prompt pure specular reflection component subtracted, are presented in Fig. 4(b). These dependencies represent time-averaged spectra of the monochromatic seed, which can be generated through S-FBD. Typical spectral widths are about 100-meV, suitable for seeding FEL pulses with a duration of a few tenths of fs. The peak value of the S-FBD intensity is at the critical angle of total reflection $\Phi = 22$ mrad, see also Fig. 4(d).

Time dependencies of S-FBD, representing the intensity of the monochromatic seed at different delays, are presented in Fig. 4(c), for different glancing angles of incidence Φ. At a 20-fs delay, typically used for self-seeding, the intensity of S-FBD in $SiO_2(10\bar{1}0)$ is comparable to the intensity of FBD in C(004) for 8.3 kev x-rays [3], maybe a factor 4 lower. Still, it is two orders of magnitude higher than what one could obtain from a 10-μm thick SiO_2 crystal in FBD mode at the same time delays, as can be seen from in Fig. 3(c).

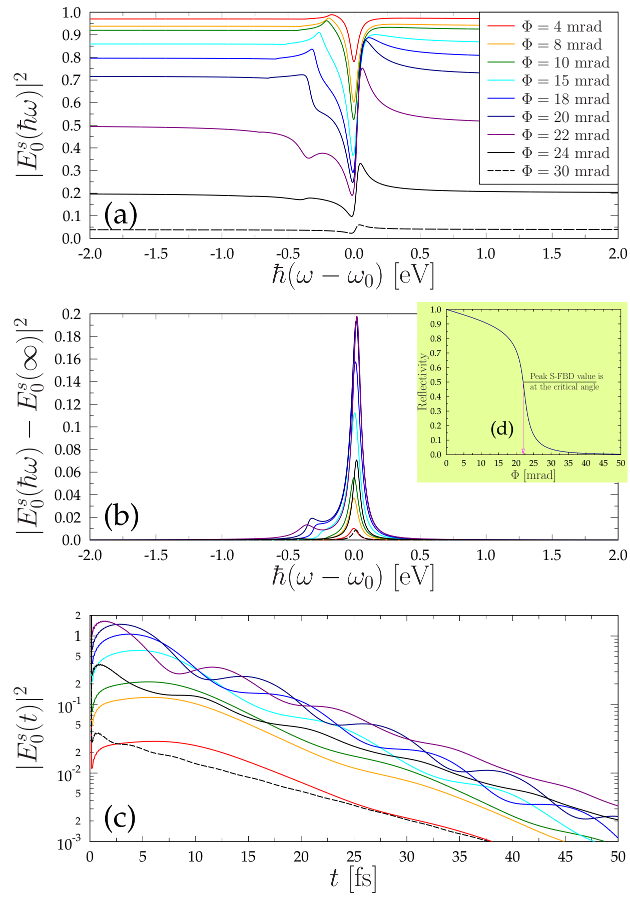

Figure 4: Spectral (a)-(b) and time (c) dependencies of forward Bragg diffraction under specular reflection conditions (S-FBD) in SiO_2 for x-rays with photon energies $\hbar\omega$ in the vicinity of $\hbar\omega_0$=1.46 keV, the nominal energy of the $(10\bar{1}0)$ Bragg diffraction at $\theta = 86.1°$.

REFERENCES

[1] J. Feldhaus, E.L. Saldin, J.R. Schneider, E.A. Schneidmiller, and M.V. Yurkov. *Opt. Commun.*, 140:341, 1997.

[2] Gianluca Geloni, Vitali Kocharyan, and Evgeni Saldin. A novel self-seeding scheme for hard x-ray FELs. *Journal of Modern Optics*, 58:1391–1403, 2011.

[3] J. Amann, W. Berg, V. Blank, F.-J. Decker, Y. Ding, P. Emma, Y. Feng, J. Frisch, D. Fritz, J. Hastings, Z. Huang, J. Krzywinski, R. Lindberg, H. Loos, A. Lutman, H.-D. Nuhn,

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D. Ratner, J. Rzepiela, D. Shu, Yu. Shvyd'ko, S. Spampinati, S. Stoupin, S. Terentiev, E. Trakhtenberg, D. Walz, J. Welch, J. Wu, A. Zholents, and D. Zhu. Demonstration of self-seeding in a hard-x-ray free-electron laser. *Nature Photonics*, 6, 2012.

[4] A. M. Afanas'ev and M. K. Melkonyan. X-ray diffraction under specular reflection conditions. Ideal crystals. *Acta Cryst.*, A39:207–210, 1983.

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