MEASUREMENT OF SPATIAL DISPLACEMENT OF X-RAYS IN CRYSTALS FOR SELF-SEEDING APPLICATIONS

PAUL SCHERRER INSTITUT

SwissFEL

http://www.psi.ch/swissfel/

A. Rodriguez-Fernandez[1], S. Reiche[1], B. Pedrini[1], and K. D. Finkelstein[2]

1SwissFEL, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

2 CHESS, Cornell University, Ithaca, New York, USA

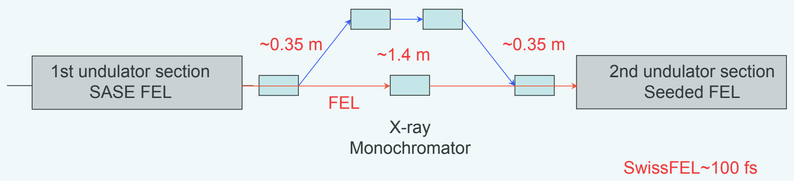
Single Crystal Hard X-ray Self-Seeding

Abstract

Free-electron laser (FEL) radiation arises from shot noise in the electron bunch, which is amplified along the undulator section and results in X-ray pulses consisting of many longitudinal modes [1]. The output bandwidth of FELs can be decreased by seeding the FEL process with longitudinally coherent radiation. In the hard x-ray region, there are no suitable external sources. This obstacle can be overcome by self-seeding. The X-ray beam is separated from the electrons using a magnetic chicane, and then monochromatized. The monochromatized X-rays serve as a narrowband seed, after recombination with the electron bunch, along the downstream undulators. This scheme generates longitudinally coherent FEL pulses.

Geloni et al. [2] have proposed monochromatization based on Forward Bragg Diffraction (FBD), which introduces a delay of the narrowband X-rays pulse of the order of femtoseconds that can be matched to the delay of the electron bunch due to the chicane. Unfortunately, the FBD process produces a small transverse displacement of the X-ray beam, which results in the loss of efficiency of the seeding process [3,4]. Preliminary results from an experiment performed at Cornell High Energy Synchrotron Source (CHESS) seem to confirm the predicted transverse displacement, which is therefore to be taken into account in the design of self-seeding infrastructure for optimizing the FEL performance.

Why Self-Seeding?



SwissFEL~100 fs

Self-Seeding advantages:

- Increment of the Longitudinal Coherence.
- Improvement of the FEL brilliance.
- Stabilization of pulse to pulse the central wavelength.
- Smoothening of the temporal pulse shape.
- Reduction of the gain length.

Chicane functions:

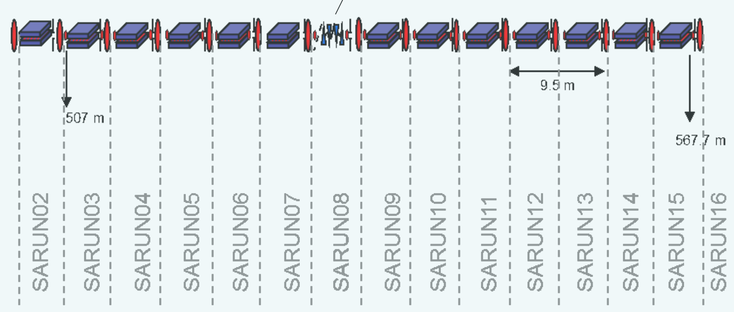
- Separates the electron and photon beam.
- Delays the electron beam to overlap with the monochromatic radiation.
- Spread out the electron bunching.

Self-Seeding at SwissFEL

Aramis Line

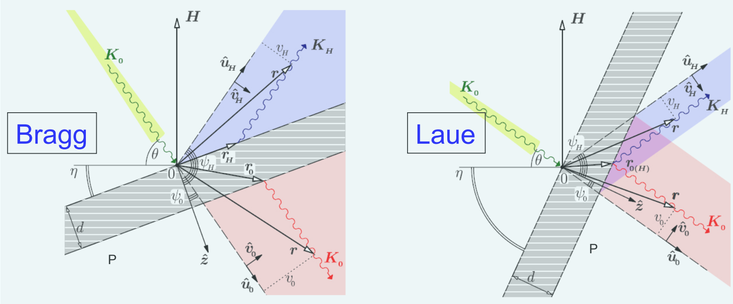
U15 Undulators
gap 3.2 – 5.5 mm
λ_u = 15 mm; K= 1.2;
L_U= 62 m

Self Seeding Chicane (10 A dipoles; 0.22 deg; 20 -200 fs)



Previous Work

Forward Bragg Diffraction



$$I_{\mathcal{H}}(\boldsymbol{r},t) \propto |\mathcal{E}_{\mathrm{i}}|^2 |G_{0\mathcal{H}}(\xi_{\mathcal{H}})|^2 \Pi^2(v_{\mathcal{H}} - \tau_{\mathcal{H}} c\cot\theta)$$

$$G_{0H}(\xi_H) = \mathrm{i}\frac{\mathcal{G}}{\mathcal{T}_\Lambda}\frac{J_1(\xi_H/\mathcal{T}_\Lambda)}{\xi_H/\mathcal{T}_\Lambda}\mathrm{e}^{-\mathrm{i}w_H\omega\xi_H} \qquad G_{0H}(\xi_H) = -\mathrm{i}\frac{\mathcal{C}\mathcal{G}}{2\mathcal{T}_\Lambda}J_0\left(\sqrt{\xi_H/\mathcal{T}_0}\right)\mathrm{e}^{-\mathrm{i}w_H\omega\xi_H}$$

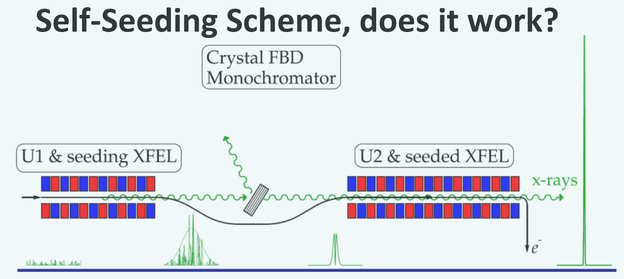
$$\tilde{G}_{00}(\xi_0) = -\frac{\mathcal{C}}{2\mathcal{T}_0}\frac{J_1\left[\sqrt{\frac{\xi_0}{\mathcal{T}_0}\left(1+\frac{\xi_0}{\mathcal{T}_d}\right)}\right]}{\sqrt{\frac{\xi_0}{\mathcal{T}_0}\left(1+\frac{\xi_0}{\mathcal{T}_d}\right)}}\mathrm{e}^{-\mathrm{i}w_H\omega\xi_0} \qquad \tilde{G}_{00}(\xi_0) = \frac{\mathcal{C}}{2\mathcal{T}_0}\frac{J_1\left(\sqrt{\xi_0/\mathcal{T}_0}\right)}{\sqrt{\xi_0\mathcal{T}_0}}\mathrm{e}^{-\mathrm{i}w_H\omega\xi_0}$$

$$\mathcal{T}_\Lambda = \frac{2\tilde{\Lambda}_H\sin^2\theta}{c|\gamma_H|} \equiv \mathcal{T}_\Lambda^{(s)}\sqrt{|b|}\sin\theta \qquad \mathcal{T}_\Lambda^{(s)} = 2\tilde{\Lambda}_H^{(s)}/c \qquad \mathcal{H} = (0,H)$$

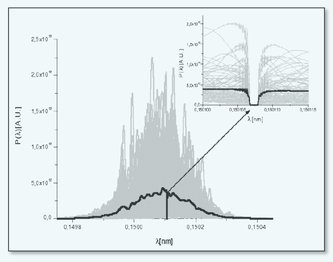
$$\mathcal{T}_0 = \mathcal{T}_\Lambda/\mathcal{A} = \frac{2[\tilde{\Lambda}_H^{(s)}]^2}{c(d/\gamma_0)}$$

R.R Lindberg and Y. Shvyd'ko
Phys. Rev. ST Accel. Beams 15, 100702 (2012)

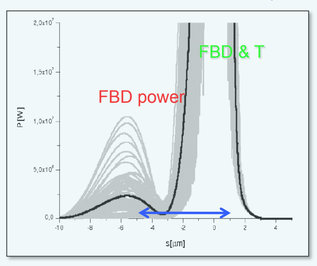
Self-Seeding Scheme, does it work?



FEL spectrum after the Seeding crystal



Power distribution after diamond crystal

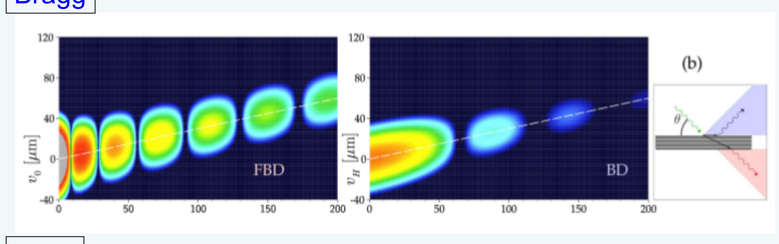


G. Geloni et al.
Journal Modern Optics 58 1391 (2011)

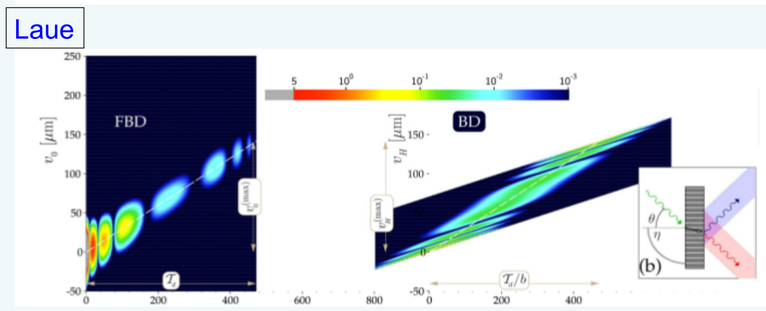
Transversal Displacement of FWD signal

$$\Delta x_0 = c\tau\cos(\theta)$$

Bragg



Laue



R.R Lindberg and Y. Shvyd'ko
Phys. Rev. ST Accel. Beams 15, 100702 (2012)

Experimental Setup & Calculations

Dynamical Theory of Diffraction

$$\mathrm{A}_{0|P} = \mathrm{R}_0\mathrm{A}_{0|\mathrm{Q}} - \underbrace{\int_A^Q d\xi' \mathrm{R}_0(\xi,\xi;\xi',\xi')\frac{ik_0\chi_h}{2\sin(\theta)}\mathrm{A}_h}_{(2)} - \underbrace{\int_A^Q d\xi'\,\mathrm{A}_0(\xi',\xi')\frac{\partial}{\partial\xi'}\mathrm{R}_0(\xi,\xi;\xi',\xi')\Big|_{\xi'=\xi'}}_{(3)}$$

- $A_{0|P}$ describe the wave that leaves the rare surfaces P.
- *h* denotes reciprocal lattice vectors inside the crystal that satisfy the diffraction condition.
- The R_0 denotes Rithe forward diffracted signal at the rear and front surfaces.
- R_0 denotes the well-known Riemann function from the dynamical theory.
- k_0 is the modulus of the x-ray wavevector.
- χ_h is *h*-Fourier component of crystal polarizability

The third term in the approximation is related to the signal leaving the crystal between 0 < ct < 300, in this interval is where the self seeding process will take place take place.

$$\mathrm{E}_{0|P|1} = \frac{1}{4\pi\sin(\theta)}e^{ik_0\chi_h(d+c\tau/\sin(\theta))/2\sin(\theta)}e^{-\frac{[x_0-c\tau\cot(\theta)]^2}{4\sigma_x^2}}$$

$$(1)\quad \times\left\{J_0\left[2\pi\sqrt{\frac{c\tau}{2\sin(\theta)}\left(d+\frac{c\tau}{2\sin(\theta)}\right)}\Big/\Lambda\right] + \frac{c\tau}{d2\sin(\theta)+c\tau}J_2\left[2\pi\sqrt{\frac{c\tau}{2\sin(\theta)}\left(d+\frac{c\tau}{2\sin(\theta)}\right)}\Big/\Lambda\right]\right\}$$

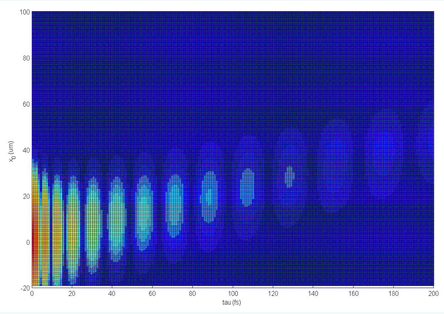
$$\mathrm{E}_{0|P|2} = \frac{k_0^2\chi_h\chi_{\bar{h}}}{\sin^2(\theta)}e^{ik_0\chi_h(d+c\tau/\sin(\theta))/2\sin(\theta)}e^{-\frac{[x_0-c\tau\cot(\theta)]^2}{4\sigma_x^2}}$$

$$(2)\quad \times\left\{J_0\left[2\pi\sqrt{\frac{c\tau}{2\sin(\theta)}\left(d+\frac{c\tau}{2\sin(\theta)}\right)}\Big/\Lambda\right] + \frac{c\tau}{d2\sin(\theta)+c\tau}J_2\left[2\pi\sqrt{\frac{c\tau}{2\sin(\theta)}\left(d+\frac{c\tau}{2\sin(\theta)}\right)}\Big/\Lambda\right]\right\}\frac{J_1[\pi(c\tau)/\Lambda]}{\pi(c\tau)/\Lambda}$$

$$\mathrm{E}_{0|P|3} = \frac{d\pi^2}{\Lambda^2\sin(\theta)}e^{ik_0\chi_h(d+c\tau/\sin(\theta))/2\sin(\theta)}e^{-\frac{[x_0-c\tau\cot(\theta)]^2}{4\sigma_x^2}}$$

$$(3)\quad \times\frac{J_1\left[\pi\sqrt{c\tau\left(2d/\sin(\theta)+c\tau/\sin^2(\theta)\right)}/\Lambda\right]}{\pi\sqrt{c\tau\left(2d/\sin(\theta)+c\tau/\sin^2(\theta)\right)}/\Lambda}$$

Simulations



Forward Bragg Diffraction using (3)

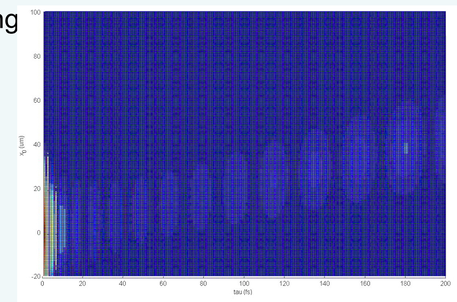
Diamond

- Bragg reflection (400)
- Energy 10 keV
- Thickness 600 μm
- Beam size 10 μm

Forward Bragg Diffraction using (1+2+3)

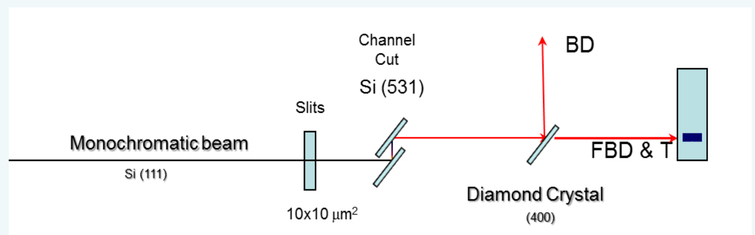
Diamond

- Bragg reflection (400)
- Energy 10 keV
- Thickness 600 μm
- Beam size 10 μm

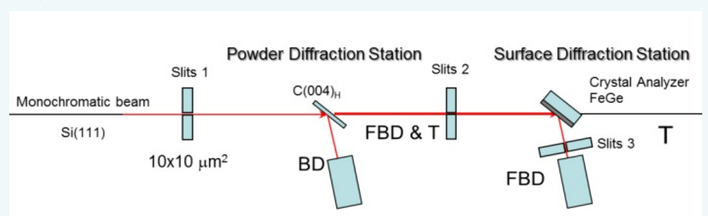


Experimental Setup

C-Line, CHESS

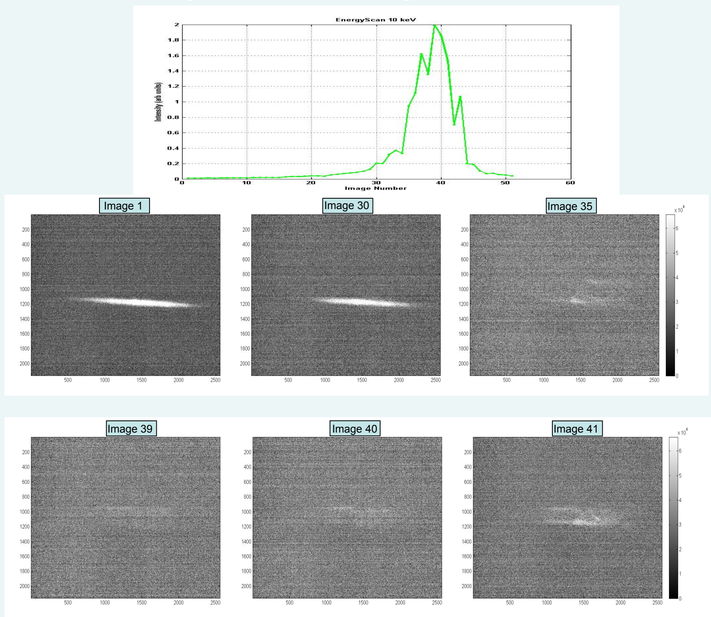


MS-Line, SLS

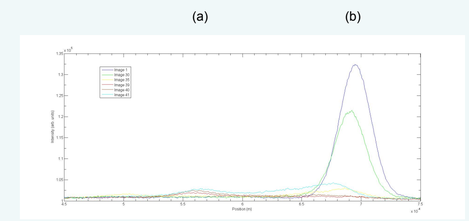


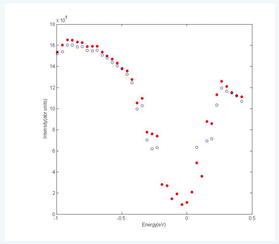
Latest Experimental Results

Experimental Displacement



Results & Discussion

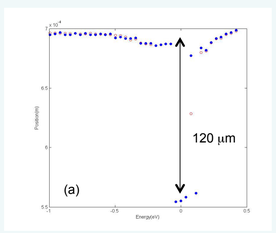


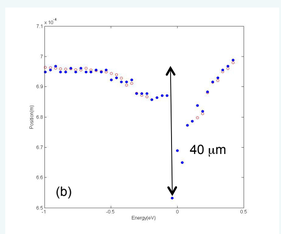


Two peaks are observed:

- The Initial transmitted beam, which is displaced while approaching the Bragg condition, we can assume that this displacement is related to the FWD translation. The total displacement of the first peak is around 40 μm.
- A Second maximum is observed near 10 keV. This second peak can be related to the 2 term in the approximation and is desplaced by 120 μm from the initial first peak.

(Time speaking this second maximum will appear at times much larger than 200 fs, so it should not be considered for self-seeding studies).





Conclusions & Outline

Conclusion

- The initial step in the study of the FWD diffraction has been performed for its future application at self-seeding FEL. It has been observed that in the case of 600 μm thick diamond single crystals a transvers displacement of the order of 40 μm can be expected.

Outline

- The future experiment will be performed:
  - Different diamond plates with thicknesses of 100, 200, 500 & 600 μm.
  - Different Bragg reflections (220), (400) and (311) for both Laue and Bragg geometries.

REFERENCES

[1] J. S. Wark and R. W. Lee, J. Apply. Crystallogr. 32, 692 (1999)
[2] G.Geloni, V. Kocharyan and E. Saldin DESY report 10-053 (2010).
[3] Y. Shvyd'ko and R. Lindberg Phys. Rev. ST Accel. Beams 15, 100702 (2012)
[4] R. R. Lindberg and Y. V. Shvyd'ko, Phys. Rev. ST Accel. Beams 15, 050706 (2012)

37th International FEL Conference: 2015, 23-28 August, Daejeon