XFEL-Oscillator Option for the European-XFEL.

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My Objectives.

- Issues to be clarified prior to a full proposal for an XFELO @ European XFEL
  - Parameter studies/simulations
  - Thermal issues \( \Rightarrow \) combine FEL results (e.g. FLASH/LCLS) with simulation of our XFELO
  - Mechanical tolerances \( \Rightarrow \) make an appropriate experiment using a real X-ray beam + Bragg crystals
Motivation.

Requirements on a XFELO

- No cw-machine \( \Rightarrow \) Saturation during one pulse train
- High repetition rate for a suitable resonator length (Here 4.5 MHz)
- Required beam parameter: low emittance and energy spread.
  Design: \( E_B = 17.5 \) GeV, \( \Delta E = 2.5 \) MeV, \( \varepsilon_n = 1.4 \) mm mrad

European-xFEL beam parameter meets this requirements
Motivation for a XFELo.

Comparison

Characteristics of a XFELo-pulse

- x-ray pulse $\lambda \approx 10^{-10}$ m
- Bandwidth $\Delta \lambda / \lambda \approx 10^{-6}$
- Temporal and transverse coherence
- High peak brilliance $10^{35}$ Photons s mm$^{-2}$ mrad$^{-2}$ 0.1%BW
- Stable output power

Characteristics of a XFEL pulse

- x-ray pulse $\lambda \approx 10^{-9}$ m – $0.8 \cdot 10^{-10}$ m
- Bandwidth $\Delta \lambda / \lambda > 8 \cdot 10^{-4}$
- Low temporal and full transverse coherence
- High peak brilliance $10^{33}$ Photons s mm$^{-2}$ mrad$^{-2}$ 0.1%BW

Experiments which may benefits from the XFELo pulses

- High resolution spectroscopy
- Nuclear diffraction and imaging
- X-ray photo-emission spectroscopy
- Coherent imaging with near atomic resolution (1 nm)
- X-ray photon correlation spectroscopy

Resonator Configurations.

4 Crystal Cavity

- Consist of 4 Bragg crystals
- Possibility to tune the wavelength changing the Bragg angle
- Tuning range depends in the transverse space
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![Diagram of 4 Crystal Cavity](image-url)
**Tuning Range**

Parameter

\[ \lambda = 2d \sin (\theta_B), \Delta \lambda = 2d (\sin (\theta_B + \Delta \theta) - \sin (\theta_B)) \]

**Resonator length** \(\sim 67\) m

- \(h_{min} : 0.50\) m
- \(h_{max} : 3.75\) m
- \(\Delta \Theta : 97\) mrad
- \(\frac{\Delta \lambda}{\lambda} : 6.2 \cdot 10^{-3}\)
Tuning Range.

Here $h_{min}$ not suitable small because of the undulator brace.

Assumptions:

\[
\begin{align*}
    h_{min} &= 0.5 \text{ m} \\
    h_{max} &= 3.75 \text{ m}
\end{align*}
\]
Simulation.

GINGER: Oscillator mode + Bragg crystal C444 @ 1 Å & 50% loss

Bragg Crystal limits the bandwidth of the radiation

Input parameter from TDR:

\[ E_{Beam} = 17.5 \text{ GeV}, \quad I_P = 5 \text{kA}, \quad \varepsilon_n = 1.4 \cdot 10^{-6} \text{ m rad} \]
Simulation.

GINGER: Oscillator mode + Bragg crystal C444 @ 1Å & 50% loss

\[ E_{\text{Pulse}} = 0.69 \text{ mJ} \]
\[ t_{\text{Pulse}} = 160 \text{ fs} \]
\[ P_{\text{Peak}} = 4.1 \text{ GW} \]

spectral width = 6.2 meV
out coupling = 20%
Peak Brilliance = \( 1.3 \cdot 10^{35} \frac{\text{Photons}}{\text{sm}^2 \text{ mrad}^2 0.1\% \text{BW}} \)
Heat Load for Diamond.

Solution of the Heat Equation in 2 dimensions

Thermal expansion of the crystals ⇒ Interrupt the amplification

\[ T_0 = 300 \text{ K}, \Delta T_{\text{Pulse}} = 2.3 \text{K}, E_{\text{Pulse}} = 0.7 \text{mJ}, \sigma_r = 30 \times 10^{-6} \text{m}, \text{Absorption} = 5\%, \Delta T(2.2 \mu \text{s}) = 3.3 \text{K} \]

\[ \frac{\partial u(\vec{r}, t)}{\partial t} = a \Delta u(\vec{r}, t) \]

- Constant Parameter
- Thermal Diffusivity:

\[ a = \frac{\lambda}{\rho c_p} \approx 1.4 \times 10^3 \frac{\text{mm}^2}{\text{s}} \]
Heat Load for Diamond.
Solution of the Heat Equation in 2 dimensions

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\[ \Delta T = 3.3 \text{ K} \]
⇒ correspond to a shift of the center of the rocking curve of 40 meV

Energy width (FWHM) of the rocking curve of Diamond ≈ 20 meV
Heat Load for Diamond.

Solution of the Heat Equation in 2 dimensions

Thermal expansion of the crystals ⇒ Interrupt the amplification

\[ T_0 = 100 \text{ K}, \Delta T_{\text{Pulse}} = 26.0 \text{ K}, E_{\text{Pulse}} = 0.7 \text{ mJ}, \sigma_r = 30 \times 10^{-6} \text{ m}, \text{Absorption} = 5\%, \Delta T(2.2 \mu s) = 1.1 \text{ K} \]

Heat equation

\[
\frac{\partial u (\vec{r}, t)}{\partial t} = a \Delta u (\vec{r}, t)
\]

- Constant Parameter
- Thermal Diffusivity:

\[ a = \frac{\lambda}{\rho c_p} \approx 5 \cdot 10^4 \text{ mm}^2 / \text{s} \]
Heat Load for Diamond.

Solution of the Heat Equation in 2 dimensions

Thermal expansion of the crystals ⇒ Interrupt the amplification

\[ T_0 = 100 \text{ K}, \Delta T_{\text{Pulse}} = 26 \text{ K}, \ E_{\text{Pulse}} = 0.7 \text{ mJ}, \ \sigma_r = 30 \times 10^{-6} \text{ m}, \ \text{Absorption} = 5\%, \ \Delta T(2.2 \mu\text{s}) = 1.1 \text{ K} \]

\[ \Delta T = 1.1 \text{ K} \]
⇒ correspond to a shift of the center of the rocking curve of 1.4 meV

Energy width (FWHM) of the rocking curve of Diamond \( \approx 20 \text{ meV} \)
Angular tolerances.

Calculated with linear optics

- The angular positioning is more critical because of the long distances
- An up and down of the crystals do not change the direction of the beam
Angular tolerances.

Calculated with linear optics

Position and angle deviation: 1/10 of the beam size and divergence
\( \Rightarrow \omega_0 = 10 \, \mu m \rightarrow \Delta x = 1 \, \mu m, \, \theta = 1.8 \, \mu rad \rightarrow \Delta x' = 0.18 \, \mu rad \)

Resonator length: \( L = 67 \, m \)
Distance \( W_1 F \) \( L_1 = 15.8 \, m \)
Distance \( FW_2 \) \( L_2 = 17.5 \, m \)
Distance \( FBM_1 \) \( d_1 = 0.15 \, m \)
Stability criterion \( X_1 X_2 = 3.3 \cdot 10^{-2} \)
Focal length \( f = 14.1 \, m \)

\[ \Delta \Theta = 70 \, \text{nrad} \]
Ground tilt between two points
without cultural noise

Measured power spectral density of the ground tilt

Fitted $PSD_{\Theta}$ from 3 Hz to 1 kHz for the wave velocity $v = 800$ m/s

$$PSD_{\Theta}(\omega) = PSD_x(\omega) \left( \frac{\omega}{v} \right)$$

$$PSD_x(f) = \frac{1}{f^2} \mu m/\sqrt{Hz}$$

Measured $PSD_x$ @ PETRA

Ref:

A. N Luiten et al., Rev. Sci. Instrum. 68 (4)

K Balewski, et al, TDR PETRA
Ground tilt between two points

without cultural noise

Extrapolation to higher frequency using the formula

\[ PSD_\Theta(\omega) = PSD_x(\omega) \left(\frac{\omega}{v}\right)^2 \]

\[ \Delta x'_{rms}(\omega) = \int_{\omega}^{\infty} PSD_\Theta(\omega) \]

Ground tilt estimation during one pulse train

\[ \Delta x'(1 \text{ kHz}) \approx 0.5 \text{ nrad} \]

Verify the angle positioning of the crystals for this and for longer time scales
Test setup to verify the angular tolerances.

Where?
- X-Ray source PETRA
- 2 × 12 m long experimental hutchess
- Initial photon flux $> 10^{11}$ Photons/s with $10^{-4}$ rel. bandwidth

What?
- Stabilize the crystals to the calculated tolerances of 70 nrad
- Measuring bandwidth $\sim 1$ kHz
- Feedback to correct the mirror position
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How?
- Transmissive, high resolution xBPMs
- Bragg Crystals Si 444 @ 8 keV
- Crystals mounted on a piezo mount

What?
- Stabilize the crystals to the calculated tolerances of 70 nrad
- Measuring bandwidth $\sim 1$ kHz
- Feedback to correct the mirror position
Test setup to verify the angular tolerances.

**XBPM:**
- Resolution $\sim 200$ nm
  - $\Rightarrow$ FMB Oxford Nano BPM release Summer '10
  - $\Rightarrow$ 4 quadrant Diamond PD still under development
- Bandwidth of $\sim 1$ kHz

\[
\begin{align*}
L &= 9 \text{ m} \\
\Delta x &= 0.5 \cdot 10^{-6} \text{ m} \\
\sigma_x &= 0.2 \cdot 10^{-6} \text{ m} \\
\Delta \theta &= 65.5 \text{ nrad} \pm 35 \text{ nrad}
\end{align*}
\]
Test setup to verify the angular tolerances.

Piezo actuator:

- PSM2
- Open loop resolution 4 nrad
- $f_{Res} = 4.5$ kHz

Concept:

- Components on a granite basement fixed to the ground
- Use of as less as possible components to align the crystals

For alignment of Si (444) ①:

- Rotation stage
- xy-stage
- 2 circle element

Additional alignment for Si (444) ②

- xy-stage for moving the crystal in the horizontal plane
Conclusion.

- Simulation
  - Pulse energy saturates during one pulse train
  - Peak brilliance $\approx 10^{35} \frac{\text{Photons}}{\text{sec mm}^2 \text{ mrad}^2 0.1\% \text{BW}}$

- Heat load seems to be OK
  - More detailed heat load simulation under way

- Set up the experiment
  - To verify the tolerances.
  - Using the x-ray source PETRA
  - Engineering on the way
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