XFELo X-ray Cavity Feasibility Studies

Yuri Shvyd’ko
Content

- Technical challenges

- Feasibility studies:
  - reflectivity of diamond crystals
  - heat load problem
  - nanoradian angular stabilization
  - radiation damage

- Conclusions and Outlook
XFEL Oscillator

XFELO requires:
- ultra-low-emittance ($\varepsilon_n \lesssim 10^{-7}$ m rad) electron beams,
- low-loss x-ray crystal cavity (losses $\simeq 15\%$)

$R_1, R_2 > 95\%, T_1 \simeq 4\%$

Reflectivity of Si in backscattering

Reflectivity

Si @300 K

Si @120 K
Theory predicts highest reflectivity from diamond

Very high reflectivity (in theory) due to:

- High Debye Temperature, and thus high Debye-Waller factor
- Low $Z$, low photo absorption

Reflectivity

0 5 10 15
0.75
0.8
0.85
0.9
0.95
1.0

C
@300 K

$E$ [keV]
Diamond cavity for the X-FEL Oscillator

\[ R_A \times R_B \times R_{M_1} \times R_{M_2} \simeq 0.9 \]

\[ T_A \simeq 0.04 \]
Diamond crystal and mirror reflectivity @ 12 keV

Narrow band mirrors: $\Delta E \approx 10$ meV; $\Delta E \approx \hbar/\tau_p$

$E_0 = 12.0404$ keV

C(4 4 4); L = 0.2 mm; T = 300 K

C(4 4 4); L = 0.042 mm; T = 300 K

Mirror calculations: www-cxro.lbl.gov
Two-Crystal Cavity is not Tunable

$E = E_H \cos \Theta \quad \Rightarrow \quad \text{Two-crystal scheme is not tunable.}$

Because, it is necessary to keep small $\phi \lesssim 2 \text{ mrad}$
and therefore small $\Theta \lesssim 2 \text{ mrad}$, for high reflectivity of the mirrors.
A four-crystal (A,B,C, and D) x-ray optical cavity allows photon energy \( E \) tuning in a broad range by changing the incidence angle \( \Theta \).

X-ray Optics:

- Quality of diamond crystals: is the theoretical reflectivity achievable?

- Heat load problem (reflection region variations $\lesssim 1$ meV).

- Angular stability: $\delta \theta \lesssim 10$ nrad (rms)

  Spatial stability: $\delta L \lesssim 3$ $\mu$m (rms) $\rightarrow$ $\delta L/L \lesssim 3 \times 10^{-8}$

- Radiation damage
Quality of Diamond crystals
Quality of Diamond crystals

Required diamond crystals:

- high quality (dislocation free, etc.)
- thickness: 20 – 2000 µm
- small suffice: ≃ 1 mm²

Still open question: is the theoretical reflectivity achievable?

White beam topograph in transmission

Härtwig, 2008 (ESRF)

Dislocation free areas of 4x4mm² and more!!!

110-oriented plate
Experiments, 30-ID @ APS

- Undulator
- X-ray bandwidth: 100 eV
- C(111) cooled monochromator
  - Bandwidth: 1.7 eV

- 2 × Si(220) at 300 K
- Si(15 11 9) channel-cut at 300 K
- 2 × Si(220)
- T. Toellner

High-resolution monochromator
- Energy: E = 23.7 keV
- (111) reflection
- Θ = 2 × 10⁻⁴
- (995) reflection
- L ≈ 10 m
- APD diamond

Bandwidth
- ΔE ≈ 1 meV

Spectral Width and Reflectivity: Theory

$C(995), E_H = 23.765 \text{ keV}$

Reflectivity, $R$

$E - E_0, [\text{meV}]$

$R_{\text{theory}} = 91\%$

$\Delta E = 2.9 \text{ meV}$

$L_{\text{crystal}} = 415 \mu\text{m}$

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FLS2010, SLAC, March 1, 2010
Spectral Width and Reflectivity: Experiment

C(995), $E_H = 23.765$ keV

Beams footprint $\simeq 1 \text{ mm}^2$

Reflectivity, $R$

$\delta E = 1.5 \text{ meV}$

$\delta E = \frac{hc}{2L_{\text{crystal}}}$

$d_{\text{crystal}} = 415 \pm 5 \mu m$

$R_{\text{theory}} = 91\%$

$R_{\text{experiment}} = 87\%$

$R$, $L$, and $\Delta E$ are interconnected.

Smallness of $\Delta E$ is a hallmark of high quality crystal.
Spectral Width and Reflectivity Map

(a) Spectral width, $\Delta E/\Delta E_{\text{min}}$

(b) Reflectivity, $R/R_{\text{max}}$


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Synthetic diamond crystals are available with theoretically high reflectivity and sufficiently large in size for XFELO cavity applications.
Heat Load Problem
Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta \delta T$.

Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.

Incident power $\simeq 50 \, \mu J$/pulse.
Absorbed power: $\simeq 1 \, \mu J$/pulse (2%).
Footprint: $\simeq 100 \times 100 \, \mu m^2$

Is it a problem?
Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta \delta T$.

Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.

- Big temperature jump $\delta T$ after the x-ray pulse arrival.
- $T=300K$: Big temperature spread by the arrival of heat.

H. Sinn simulations

Diamond Temperature $T$ [K]

Photon Energy Spread $\delta E$ [meV]
Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta\delta T$.

Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.

- Big temperature jump $\delta T$ after the x-ray pulse arrival.
- $T=300$K: Big temperature spread by the arrival of the next x-ray pulse.
- $T=100$K: Negligible temperature spread by the arrival of the next x-ray pulse.

H. Sinn simulations

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**Requirement:** $\delta E \lesssim 1$ meV, when the next pulse arrives.

- Big temperature jump $\delta T$ after the x-ray pulse arrival.
- $T=300K$: Big temperature spread by the arrival of the next x-ray pulse.
- $T=100K$: Negligible temperature spread by the arrival of the next x-ray pulse.

**Reasons:**
1. High temperature diffusivity $D$
2. Low temperature expansion $\beta$

**Solution:** Maintain diamond at $T < 100$ K!
Diamond Thermal Expansion

Thermal expansion $\beta$, $[K^{-1}]$

- $10^{-9}$
- $10^{-8}$
- $10^{-7}$
- $10^{-6}$

Temperature $T$, $[K]$

Experiment 1 (March 09)
Experiment 2 (May 09)

4.0 $\times 10^{-14} T^3$

Polynomial fit

Stoupin, Shvyd’ko, PRL104, 085901 (2010)
Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E / E = \beta \delta T$.

Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.

Solution: Maintain diamond at $T < 100$ K!
Angular & Spatial Stability

Required angular stability: $\delta \theta \lesssim 10 \text{ nrad (rms)}$

Required spatial stability: $\delta L \lesssim 3 \text{ \mu m (rms)} \Rightarrow \delta L/L \simeq 3 \times 10^{-8} \ (L = 100 \text{ m})$
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Required spatial stability: $\delta L \lesssim 3 \mu\text{m (rms)} \Rightarrow \delta L/L \simeq 3 \times 10^{-8} \,(L = 100 \text{ m})$

Solution: **Null-detection hardware feedback.** (LIGO prototype)

X-ray intensity: linear response to small angular oscillations is proportional to angular deviation from the maximum of the rocking curve.
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**X-ray intensity:** linear response to small angular oscillations is proportional to angular deviation from the maximum of the rocking curve.

**Feedback:** correction signal is extracted using lock-in amplification.
HERIX Monochromator Stability Region

- Intensity [a.u.]
- Voltage [V]
- Region of stability $\Delta \theta = 50$ nrad
- FWHM $\Delta \theta = 500$ nrad
- $\pm 75$ mV

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HERIX Monochromator Stabilization

T. Toellner, D. Shu

Yu. Shvyd’ko

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HERIX Monochromator Stabilization

\[ \theta_3 \]

\[ \Theta_0 \]

\[ \Theta_1 \]

\[ \approx 15 \text{ nrad (rms)} \] stabilization was demonstrated

Stoupin, Lenkszus, Laird, Goetze, K-J Kim, Shvyd’ko, RSI (submitted)

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Radiation damage in diamond
Radiation damage in diamond

**XFEL0 generates:**

50µJ/pulse @ 12 keV with \( \simeq 1 \) MHz rep. rate

**Footprint:** \( A = 1.6 \times 10^{-4} \text{ cm}^2 \) (rms)

**Flux** \( \simeq 2 \times 10^{20} \text{ ph/s/cm}^2 \)

**Time to ionize carbon atom with 100% probability:** \( T \simeq 250 \text{ s} \)

Can this produce irreversible changes in the perfect crystal lattice structure?
Radiation damage in diamond

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**Time to ionize carbon atom with 100% probability:** $T \simeq 250 \text{ s}$  

Robin Santra

**APS undulators generate:**

**Flux** $\simeq 5 \times 10^{17} \text{ ph/s/cm}^2$

**Time to ionize carbon atom with 100% probability:** $T' \simeq 10^5 \text{ s} \simeq 1 \text{ day}$

Graphitization of the surface layer of the diamond crystal is observed after several days of operations. Though, no significant degradation in the performance of the high-heat-load monochromator is observed after a year of operations.
How to mitigate radiation damage in diamond?

- Operate diamond at cryogenic temperatures.
- Use isotopically pure $^{12}\text{C}$ crystals. Laser damage threshold is more than order of magnitude higher for isotopically pure diamond. Anthony et al, PRB, 42 1104 (1990)
- Apply electric fields to keep the electrons in diamond (K-J. Kim)
- ....
X-ray Optics:

- **Quality of diamond crystals:**
  is the theoretical reflectivity achievable? ✓

- **Heat load problem:** reflection region variations $\lesssim 1$ meV. ✓

- **Angular stability:** $\delta \theta \lesssim 10$ nrad (rms) ✓
  Spatial stability: $\delta L \lesssim 3$ $\mu$m (rms)  $\rightarrow$  $\delta L/L \lesssim 3 \times 10^{-8}$

- **Radiation damage** ?

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