An X-Ray FEL Oscillator: Promises and Challenges

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Era of Hard X-Ray (\( \lambda \approx 1 \text{ Å} \)) FEL has Arrived

**LINAC Coherent Light Source (LCLS)**
- **Project start**: 1999
- **LCLS**: August, 2008
- **LCLS, April 2009**
  - \( I = 500 \text{ A} \)
  - \( I = 3000 \text{ A} \)
- **User experiment**: April 10, 2009
- **September, 2009**

**European XFEL Facility**
- **2011**
  - RIKEN/SPring-8 XFEL
- **2014**
  - **KJK KEK Dec 21, 2009**
LCLS: Single-pass, high-gain FEL amplifying initial noise → High transverse coherence but marginal temporal coherence

Transverse mode

- z = 25 m
- z = 37.5 m
- z = 50 m
- z = 90 m
With the LCLS demonstration of e-beam modulation @ Å-scale, further FEL capabilities can be explored

- **SASE**
  - Ultrafast (down to atto-second ?) regime

- **Seeded harmonic amplifier**
  - High harmonics (e.g., via echo-assisted technique) for coherent soft x-rays

- **Oscillator**
  - Ultrahigh spectral purity and high average brightness for hard x-rays
Hard X-Ray FEL Oscillator

- Store an X-ray pulse in a Bragg cavity ➞ multi-pass gain & spectral cleaning
- Provide meV bandwidth
- MeV pulse repetition rate ➞ high average brightness
- Zig-zag path cavity for wavelength tuning

Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (KJK, S. Reiche, Y. Shvyd’ko, PRL 100, 244802 (2008))
Diamond backscattering: High reflectivity and narrow bandwidth

Courtesy of Yuri Shvyd’ko
**Tunable X-ray Cavity**

- **Two crystal scheme**
  - a very limited tuning since $\theta$ must be kept small

- **A tunable four crystal scheme**
  - Any interesting spectral region can be covered by one chosen crystal material
  - Simplify the crystal choice → Diamond as highest reflectivity & best mechanical and thermal properties

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R. M.J. Cotterill, APL, 403,133 (1968)
KJK & Y. Shvyd’ko, PRSTAB (2009)
Brightness of Hard X-Ray Sources

![Brightness of Hard X-Ray Sources Graph](image-url)
**XFEL Parameters**

- **Electron beam:**
  - Energy 7 GeV
  - Bunch charge ~ 25-50 pC → *low intensity*
  - Bunch length (rms) 1 (0.1 ps) → Peak current 20 (100) A
  - Normalized rms emittance < 0.2 (0.3) mm-mr, energy spread (rms) ~ 2 × 10^{-4}
  - Constant bunch rep rate @ ~1 MHz

- **Undulator:**
  - L_u = 60 (20) m, λ_u ~ 2.0 cm, K = 1.0 – 1.5

- **Optical cavity:**
  - 2- or 4- diamond crystals and focusing mirrors
  - Total round trip reflectivity > 85 (50) %

- **XFEL output:**
  - 5 keV → 25 keV
  - Bandwidth: Δω/ω ~ 1 (5) × 10^{-7}, pulse length (rms) = 500 (80) fs
  - # photons/pulse ~ 1 × 10^9

*Blue color indicates short-pulse mode for relaxed tolerances*
XFELo will revolutionize the hard x-ray techniques developed at storage-ring-based light sources and find new applications in areas complementary to SASE

- Inelastic x-ray scattering
- Mössbauer spectroscopy
  - $10^3$/pulse, $10^9$/sec Mössbauer photons (14.4 keV, 5 neV BW)
- Bulk-sensitive Fermi surface study with HAXPES
- Time-resolved methods (0.1-1 ps)
- X-ray imaging with near atomic resolution (~1 nm)
  - Smaller focal spot with the absence of chromatic aberration
- X-ray photon correlation spectroscopy
  - $10^{15}$ photons/sec is a game changer, better time structure than LCLS, t-coherence is a huge advantage (Alec Sandy)


**XFELO Modeling**

- **Analytical (KJK, R. Lindberg)**
  - Gain calculation, super-mode theory for evolution in optical cavity

- **GENESIS (S. Reiche)**
  - \((x,y)\) asymmetric, single wavefront \(ightarrow\) slow: 1 month computing from noise to saturation

- **Reduced 1-D FEL code (R. Lindberg)**
  - Transverse dependence integrated out assuming Gaussian mode
  - Fast and reasonable agreement with GINGER and GENESIS

- **GINGER (W. Fawley, R. Lindberg, Y. Shvyd’ko, ..)**
  - \((x,y)\) symmetric \(\rightarrow\) much faster than GENESIS
  - Implemented a correct crystal response

KJK KEK Dec 21, 2009
Crystal Phase Shift and Cavity Length Detuning

- Amplitude reflectivity for near normal incidence x-rays
  \[ r(y) = y - i \sqrt{1 - y^2} \approx -i e^{iy} \]
  \[ y = \frac{1}{\chi_H} \left[ \frac{2(E - E_H)}{E_H} + \chi_0 \right] \]

- XFELO works near \( y \approx 0 \). The angular spread effect is small

- \( \omega \)-dependent phase shift
  \[ \exp(i\omega \tau) \quad c\tau = \frac{\lambda_H}{2\pi|\chi_H|} \]

- can be corrected by cavity length adjustment
Approach to high spectral purity is expedited by spectral filtering at crystals.
Ginger Simulation of XFEL Spectrum After 500 Passes
(Two Diamond Crystal Cavity, 50 &mu;m and 200 &mu;m, R. Lindberg)
**Electron Gun Technologies**

- The LCLS S-band NC RF PC demonstrated ultra-low $\varepsilon_x$
  $\varepsilon_x = 0.14 \times 10^{-6}$ m, $Q = 20$ pC, $f_b = 120$ Hz

- The PITZ L-band NC RF PC may be suitable for a pulsed XFELO:
  $\varepsilon_x = 0.3-0.4 \times 10^{-6}$ m, $Q = 100$ pC, $f_b = 1$ MHz, $t_{macro} = 800$ $\mu$s, $f_{macro} = 10$ Hz

- Cornell DC PC for ERL
  $\varepsilon_x = 0.2 \times 10^{-6}$ m, $Q = 20$ pC, $f_b = 1.3$ GHz, CW
  - Requires 750 kV DC voltage?

- SCRF guns (FZD, HZB, Peking U, WIFEL)
  - CW but $\varepsilon_x > 1 \times 10^{-6}$ m

- LBNL 200 MHz, NC RF Gun (CW) (design)
  - Could be configured for XFELO requirements

- RIKEN/Spring-8 *thermionic*, pulsed DC
  - 500 kV @ 60 Hz, $\varepsilon_x = 0.6 \times 10^{-6}$ m with 3 mm diameter
A Novel Injector Concept for XFEL O

- Current paradigm of injector design: *laser driven rf photo-cathode*
- For low intensity & ultra-low emittance → *thermionic cathode*
- Inspired by the SCSS/Spring-8 success of pulsed DC gun
  - T. Shintake and K. Togawa
- Low frequency RF gun-cavity for high, constant repetition rate
- Performance
  - Normalized rms emittance < 0.2 (0.3) mm-mr
  - Bunch length (rms) 1 (0.1 ps)
  - Peak current 20 (100) A
  - A constant bunch rep rate @ ~1 MHz
Critical R&D Items for an XFEL0 Injector

- Small diameter CeB6 thermionic cathode
  - 1 mm (3 mm for RIKEN/SPring-8)
- 100 MHz, 1 MV RF cavity
  - Peak accelerating field=20 MV/m below 1.8 Kilpatrick limit (1.76)
  - Similar to LBNL 187 MHz cavity but without vacuum holes
- Addressing back-bombardment issue
  - Off-centered cathode or a magnet to deflect returning electrons
  - Cathode heating by ns laser pulse with MHz rep rate
Technology R&D for XFEL0
X-Ray Optics

- High quality diamond crystals
- Highly reflectivity and low phase distortion of grazing incidence focusing mirror
- Stability
- Advances in these technologies are eagerly sought after by broader synchrotron radiation community
Optical properties of available diamond crystals

Topography, R and ΔE data (Sumitomo sample, S. Stoupin & Y. Shvyd’ko)
Reflectivity and spectral width measurement at APS sector-30 in good agreement with theory

C(995)

$E_H=23.765 \text{ keV}$

S. Stoupin, Y. Shyv’dko, A. Cunsolo, A. Said, S. Huang

(Nature/Physics)
Heat Loading Issues

- As an intracavity x-ray pulse hit crystals, r-dependent temperature rise $\delta T \rightarrow$ crystal expansion $\rightarrow \delta E/E = \beta \delta T$ ($\delta L/L = \beta \delta T/\delta T$). **Is this $<10^{-7}$?**
- Yes, $T < 100K$
  - Inter-pulse $\delta E/E < 10^{-7}$ due to high thermal-diffusivity
  - Intra-pulse $\delta E/E < 10^{-7}$ due to $\beta < 10^{-7}$ and if the expansion time < pulse duration (~ps)

S. Stoupin and Y. Shvyd’ko, PRL

![Graphs showing temperature and energy changes](image-url)
Grazing Incidence, Curved Mirror

- **JTEC**
  - Developing a technique combining elastic emission machining (EEM, slow) and electrolytic in-process dressing (ELID, fast) to fabricate an “arbitrary” surface, such as ellipsoidal, to <nm height error and 0.25 mrad figure error
  - Such mirrors are sought after by “every body” in SR business

- **Other ways of focusing**
  - Curved crystal surface, CRL,..
Null-detection FB stabilization at APS Sector 30

(S. Stoupin, F. Lenkszus, R. Laird, Y. Shvy’dko, S. Whitcomb,..)

- The stability of K3 signal indicates the angular stabilization of the 3rd crystal pair within 13 nrad (rms) is achieved @ 1 Hz BW
Prototype X-Ray Cavity at the APS

- About 1/5 model of an XFEL cavity
- Adjust the distance $M_1-M_2$ to control the stability
- Adjust the round trip path length to match/mismatch the spacing (46m) between the APS x-ray pulses
- Test overall reflectivity, crystal and mirror stabilization, and transverse mode profile
Accelerator Options

- Straight SCRF linac is the most versatile but also the most expensive
  - Can also accommodate ultrafast SASE
- Recirculation will save the cost.
  - Energy recovery is not mandatory for a single XFELO due to low average power
  - The injector, accelerator, and recirculation passes should be optimized as a single system (See the following talk)

Integration with an ERL light source

1. In a straight section of the loop
2. In an additional single-ended branch

From Hajima’s talk at X’ian (Sept. 2009)