An X-Ray FEL Oscillators
(for Record-High Spectral Purity & Brightness)

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APS Users Monthly Operations Meeting

October 28, 2009
Era of Hard X-Ray ($\lambda \approx 1$ Å) FEL has Arrived

**LINAC Coherent Light Source (LCLS)**
- Project start: 1999
- LCLS, August, 2008
- LCLS, April 2009

**European XFEL Facility**
- 2014

**RIKEN/SPring-8 XFEL**
- 2011

$I=500$ A

$I=3000$ A

April 10, 2009
User experiment
September, 2009
**LCLS: Single-pass, high-gain FEL amplifying initial noise** → **Excellent transverse coherence but temporal coherence is marginal**

Transverse mode

- **z = 25 m**
- **z = 37.5 m**
- **z = 50 m**
- **z = 90 m**

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**Electron Bunch Micro-Bunching**

**Exponential Gain Regime**

**Saturation**

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**Undulator Regime**
LCLS demonstrates FEL principles work @ Å-scale. It is now time to develop optimized FEL schemes for Future Light Sources

- SASE
- Seeded harmoniuc amplifier
  - Soft X-rays
- Oscillator
(Hard) X-Ray FEL Oscillator

- An X-ray pulse is stored in a diamond cavity → multi-pass gain & spectral cleaning
- Provide transform limited BW → $1 \times 10^{-7} - 5 \times 10^{-7}$ for $\sigma_t = 1 - 0.1\text{ps} \ @ \lambda \sim 1\text{ Å}$
- Zig-zag path cavity allows wavelength tuning
- Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (K-J. Kim, S. Reiche, Y. Shvyd’ko, PRL 100, 244802 (2008))
Tunable X-ray Cavity

- Two crystal scheme has a very limited tuning since $\theta$ must be kept small
- A four crystal scheme is tunable
- 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

R. M.J. Cotterill, APL, 403, 133 (1968)
Brightness of Hard X-Ray Sources

![Graph showing the brightness of different x-ray sources across various energies.](Image)
**Major Parameters**

- **Electron beam:**
  - Energy $\uparrow 7$ GeV
  - Normalized rms emittance $< 0.2$ (0.3) mm-mr, energy spread (rms) $< 2 \times 10^{-4}$
  - Bunch charge $\sim 25$-50 pC $\rightarrow$ *low intensity*
  - Bunch length (rms) $\Delta t$ 1 (0.1 ps) $\rightarrow$ Peak current 20 (100) A
  - A constant bunch rep rate $@ \sim 1$ MHz

- **Undulator:**
  - Lu = 60 (30) m, $\lambda_u \sim 2.0$ cm, K=1.0 – 1.5

- **Optical cavity:**
  - 2- or 4- diamond crystals and focusing mirrors
  - Round trip reflectivity should be $> 85$ (50) %

- **XFELO output:**
  - 5 keV $\nless \nless$ 25 keV
  - Bandwidth: $\Delta \omega/\omega \sim 1$ (5) $\times 10^{-7}$, pulse length (rms) = 500 (80) fs
  - # photons/pulse $\sim 1 \times 10^9$

*Blue color in the above indicates short-pulse mode for relaxed tolerances*
XFELo Will Revolutionize the Techniques Developed at 3rd Gen Light Sources and Find New Applications in Areas Complementary to SASE

- High resolution spectroscopy
  - Inelastic x-ray scattering

- Moessbauer spectroscopy
  - $10^3$/pulse, $10^9$/sec Moessbauer $\gamma$s (14.4 keV, 5 neV BW)

- X-ray photoemission spectroscopy
  - Bulk-sensitive Fermi surface study with HX-TR-AR PES

- X-ray imaging with near atomic resolution (~1 nm)
  - Smaller focal spot with the absence of chromatic aberration
Technology R&D for XFEL0

- **Injector**
  - Low-intensity, ultralow emittance, CW Injector

- **X-ray optics**
  - High quality diamond crystals in a small volume (1-2) mm$^2$
    (40-100) µm
  - Highly reflectivity and low phase distortion of grazing incidence
    focusing mirror
  - Stability

*Advances in these R&Ds will benefit general accelerator and synchrotron radiation community*
Injector for XFEL0: A Novel Approach

- Current paradigm of injector design: laser driven rf photocathode
- For low intensity & ultra-low emittance → thermionic cathode inside VHF band cavity (~ 100 MHz)
- Inspired by the SCSS/Spring-8 success of pulsed DC gun (T. Shintake, K. Togawa,..)
**Injector R&D**

- **Small diameter CeB6 thermionic cathode**
  - 0.5 mm (3 mm for RIKEN/SPring-8)

- **100 MHz, 1 MV RF cavity**
  - Peak accelerating field = 20 MV/m is slightly below 1.8 $\times$ Kilpatrick limit (1.76)
  - Similar to LBNL 187 MHz cavity but with thermionic cathode and without vacuum holes

- Laser-induced cathode-heating may obviate the deflecting cavity/slits and back bombardment problem

*Courtesy: F. Sannibale*
Reflectivity and Spectral Width Measurement at APS Sector 30 in good agreement with Theory March, 2009

C(995)

$E_H = 23.765 \text{ keV}$

S. Stoupin, Y. Shvyd’ko, A. Cunsolo, A. Said, S. Huang
**Heat Load Problem?**

- As an intracavity x-ray pulse hits a crystal, r-dependent temperature rise $\delta T \rightarrow$ crystal expansion $\rightarrow \delta E/E = \beta \delta T$ ($\delta L/L=\beta \delta T/T \rightarrow \delta E/E<<10^{-7}$?)

- Due to high thermal-diffusivity, inter-pulse effect can be made small if $T<100K$ (high heat diffusivity)

- Intra-pulse effect $\delta E/E <<10^{-7}$ if the expansion time scale $<<$ pulse duration (~ps). Otherwise $\delta E/E \sim 5-10 \times 10^{-7}$

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S. Stoupin and Y. Shvyd’ko, March 2009

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[Diagram: Diamond thermal expansion vs. temperature ($T$, $K$)]

[Diagram: Diamond temperature $T$, [K] vs. Time [\mu s], Energy Spread $\delta E$, [MeV]]
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,..
The stability of IC3 signal indicates the angular stabilization of the 3rd crystal pair within 50 nrad is achieved (~1 Hz BW)
Prototype X-Ray Cavity at an APS Beamline

- About 1/5 model of an XFELO 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, transverse mode profile
**XFEL0 Study Group**

- **Modeling/Simulation**
  - R. Lindberg, W. Fawley, S. Reiche

- **Injector**
  - A. Nassiri, N. Sereno, M. Borland, G. Waldschmidt, D. Capatina, P. Ostroumov, B. Mustapha, P. Piot, S. Kondrashev, ...

- **X-ray Optics:**
  - Y. Shvyd’ko, S. Stoupin, D. Shu, A. Macrander, L. Assoufid, G. Park, ...

- **Institutions interested in collaboration**
  - RIKEN/Spring-8: Injector, X-ray optics
  - DESY: XFEL0 test at European XFEL ?
  - LBNL: 100 MHz cavity
  - KEK: XFEL0 at ERL
  - Inst. for Geology and Mineralogy (Novosibiersk) and Tech. Inst. for Superhard & Novel Carbon Materials, Moscow: Diamond