An XFEL as a High Coherence, High Average Brightness X-Ray Source

Kwang-Je Kim

ANL and the University of Chicago

September 15-16
SLAC and LBNL
California
- Basic XFELO concepts
- Some more details on FELs
- Injector-accelerator
An X-Ray FEL Oscillator (XFELO)

- A Concept for XFELO was first proposed by R. Colella and A. Luccio, Opt. Comm. 50, 41 (1984)
- Use of x-ray cavity for improving high-gain FEL coherence was considered by B. Adams and G. Materlik (1997) and Z. Huang and R. Ruth (PRL, 96, 144801, 2006)
- With the ultralow emittance beams, such as studied for ERLs, an XFELO was shown to be feasible (KJK, Y. Shvyd’ko, and S. Reiche, PRL, 100, 244802 (2008)}
Performance of XFEL-O

- Spectral range: 3 keV $<\varepsilon_\gamma< 30$ keV
- Tunable
- $10^9$ photons ($\approx 1$ $\mu$J) /pulse
  - Less by $\approx 1000$ than High gain SASE (LCLS)
- Full transverse coherence
- Temporal coherence in $\approx$ ps (rms)
  - Time resolution less by $\approx 10$ than LCLS
  - $(\Delta \nu/\nu)_{\text{FWHM}} \approx$ a few $10^{-7}$; $h\Delta \nu = $ a few meV, better by
  - Peak spectral brightness $\approx$ LCLS
- Rep rate 1-100 MHz $\rightarrow$ average spectral brightness
  $(10^{26} -10^{29})$ $\#/$(mm-mr)$^2(0.1\%\text{BW})$, higher by a factor of
  - $10^5$-$10^7$ than other future light sources considered so far, ERL-based or high-gain FEL-based
Current and Future X-Ray Sources
Science Drivers for XFEL-O

- Inelastic x-ray scattering (IXS) and nuclear resonant scattering (NRS) are flux limited experiments! *Need more spectral flux in a meV bandwidth!*

- Undulators at storage rings generate radiation with $\approx 100-200$ eV bandwidth. Only $\approx 10^{-5}$ is used, the rest is filtered out by meV monochromators.

Presently @ APS: $\approx 5 \times 10^9$ photons/s/meV (14.4 keV)

- XFEL-O is a perfect x-ray source for:
  - high-energy-resolution spectroscopy (meV IXS, neV NRS, etc.), and
  - imaging requiring large coherent volumes.
  - Expected with XFEL-O $\approx 10^{15}$ photons/s/meV (14.4 keV) with $10^7$ Hz repetition rate.
Backscattering Reflectivities

- Diamond and sapphire have high $R > 95\%$ for perfect crystals→ Small volumes from large samples
- $R$ is less for Si, but is still respectable and perfect crystals are available
- Higher performance at lower T (Sapphire @ 40K, Si @ 120 K)
- Multiple reflection for C and Si can be avoided by slightly off from exact backscattering and glancing angle mirrors
Gain and saturation

- Without electron beam focusing, gain can be analytically computed taking into account energy spread, emittance, and diffraction (KJK, 1992)
- The is optimum when $\beta_z \sim Z_R \sim L_u / (2\pi)$
- Gain decreases as intra cavity power increases
- Saturation when gain=loss

![Graph showing the relationship between gain and intra-cavity power](image)
Linear supermode analysis\textsuperscript{4,5}

After $n$ passes, the longitudinal radiation profile $E(\tau, n)$ described by

\[
\frac{\partial}{\partial n} E(\tau, n) = \frac{1}{\sigma_\omega^2} \frac{\partial^2}{\partial \tau^2} E(\tau, n) + \frac{1}{2} (g - \alpha) E(\tau, n) - \frac{g}{2} \frac{\tau^2}{2 \sigma_e^2} E(\tau, n) + \ell \frac{\partial}{\partial \tau} E(\tau, n)
\]

(linear gain) – (mirror losses)

This equation can be related to the quantum mechanical simple harmonic oscillator, with solution:

\[
E_m(\tau, n) = e^{\Lambda_m} e^{-\tau \sigma_\omega^2 \ell/2} \exp \left[ - \sqrt{g} \frac{\sigma_\omega}{2 \sigma_e} \tau^2 \right] H_m \left[ g^{1/4} \sqrt{\frac{\sigma_\omega}{\sigma_e}} \tau \right]
\]

Per pass gain $\Lambda_m \equiv \frac{1}{2} \left[ (g - \alpha) - \sqrt{g} \frac{\sigma_\omega}{\sigma_e} (2m + 1) - \frac{1}{2} \sigma_\omega^2 \ell^2 \right]$

Simulation

“One-dimensional” FEL code with z-dependent radiation-beam coupling (R. Lindberg)

- Eliminates transverse dimension by integrating over the unperturbed electron orbits and by using the Gaussian shape for optical mode and electron distribution
- Used for initial characterization of the gain and the longitudinal radiation profile from initial start-up to nonlinear saturation

GINGER (W. Fawley)

- Implemented the Bragg crystal frequency response for each pass
- Begun systematic analysis of transverse radiation characteristics and the initial start-up from noise
The Complex Amplitude Reflectivity

- Combined reflectivity of a thin (42 μ for 4% out-coupling) and a thick (200 μ) crystals.
- The ω-dependent phase shift, is due to the fact that the effective reflecting surface is inside the crystal—can be corrected by introducing an effective detuning.
- The angular dependence of the reflectivity is negligible in XFELO cases.
### 7 GeV beam @ 1Å

<table>
<thead>
<tr>
<th>Undulator:</th>
<th>( N_u = 3000 )  ( \lambda_u = 1.76 \text{ cm} )  ( K = 1.55 )  ( \text{gap} = 5 \text{ mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam:</td>
<td>( \beta_z = 10 \text{ m} )  ( \epsilon_{x,\text{norm}} = 2 \times 10^{-7} )  ( \Delta E = 1.4 \text{ MeV} )  ( I = 10 \text{ Amp} )  ( \sigma_e = 0.2 - 2.0 \text{ ps} ) (( Q = 5-50 \text{ ps} ))</td>
</tr>
<tr>
<td>Mirror:</td>
<td>\text{diamond C(444): } \Delta \lambda/\lambda = 3.4 \times 10^{-6} )  ( R = 0.94 )</td>
</tr>
</tbody>
</table>

For total loss \( \alpha = 0.15 \), (from both mirror and lens) saturated power predicted to be \( \sim 23 \text{ MW} \)

Saturated pulse is nearly gaussian, with decreasing cavity power decreasing for \( \sigma_e \sigma_\omega \) approaching unity.

Thin mirror transmits \( \sim 4\% \) of the power

\[
\sigma_e = 1.0 \text{ ps} \sim 20/\sigma_\omega \\
\sigma_e = 0.2 \text{ ps} \sim 4/\sigma_\omega
\]
GINGER results for the 7 GeV beam @ 1Å

Linear gain $g = 0.3$; Mirror losses $\alpha = 0.15$

GINGER predicts saturation power $\sim 25$ MW, which is approximately equal to theoretical estimates.
The case for Silicon Crystal

- The reflectivity is lower than diamond but significant for about 5 keV
- However, perfect crystals are available
- Can get a sufficient gain by compressing e beam to 20Å

Complex response function @ 5.56 keV
11μ x 50μ
The case for Silicon

Ginger run assuming:
- \( E=5 \text{ GeV}, \; I=20 \text{ A}, \; \tau_{\text{rms}}=1 \text{ ps}, \) \( \Rightarrow Q=50 \text{ pC} \)
  - \( \sigma_E=1.4 \text{ MeV}, \; \varepsilon_{xn}=0.2 \mu \)
- \( \lambda_U=19.6 \text{ cm}, \; N_U=1500 \)
- \( K=1.53 \)
- Mirror spacing =60 m
- Thick crystal=50 \( \mu \)
- Thin crystal=11\( \mu \) (4\% trans)
- 5\% loss each for two lenses
- Linear gain~70\%
- Power at 151 pass~30 MW

May be used for POP experiment
Two crystal scheme is not tunable since $\theta$ should be kept small for high reflectivity of the grazing incidence mirror.

A four crystal scheme is tunable by changing $h$ and $d_2$, keeping the pass length constant, and by appropriately rotating the crystals so that the incidence and reflection angles are the same.

R. Deslattes, APL, 12, 133 (1968), KJK (2008)
Optics Design of the Cavity

Rayleigh lengths $Z_1$ and $Z_2$:

$$Z_1^2 = f^2 \frac{X_1}{X_2} (1 - X_1 X_2), \quad Z_2^2 = f^2 \frac{X_2}{X_1} (1 - X_1 X_2) \quad X_i = 1 - \frac{l_i}{f}$$

Change of $w_1$ due to crystal angular error $\Delta \theta$:

$$\begin{pmatrix} \Delta x \\ \Delta x' \end{pmatrix} = \begin{pmatrix} f \\ \ell_2 \\ (1 - X_1 X_2) f \end{pmatrix} \Delta \theta$$
An example:

- \( Z_1 = 10 \text{ m} \) to maximize gain for \( L_u = 60 \text{ m} \)
- \( Z_2 = 250 \text{ m} \) to reduce the angular divergence at crystals by a factor of 5
- \( X_1X_2 = 0.1 \) so that the cavity is stable
- \( \Rightarrow f = 51.3 \text{ m}, I_1 = 1.02 \text{ m}, I_2 = 75.4 \text{ m} \)
- Choose \( h = d_2 = 1 \text{ m} \) \( \Rightarrow d_1 = 12.06 \text{ m} \)
- Require the optical axis displacements \( \Delta x \) and \( \Delta x' \) at \( W_1 \) are 1/10 of mode rms size and angle
- \( \Rightarrow \Delta \theta < 20 \text{ nr} \) (tight but better than two crystal case considered before)
- \( \Rightarrow \) May be satisfied via null detection feedback
Focusing Elements

- Focusing is necessary to adjust the cavity Rayleigh length

- Compound Refractive Lenses (CRLs) is ideal if it can be made from single crystal Be. However, loss is large with polycrystalline Be due to small angle scattering from grain boundaries.

- Grazing incidence mirrors (common in x-ray beam line of an SR facility) can provide focusing with small loss < 2%.
  - The tolerance in slope error from geometrical optical consideration is 0.25 μr appears to be feasible.
  - Wave optics calculation is planned
Repetition Rate

- $f_{\text{rep}}= 1 \text{ MHz}$ when one x-ray pulse stored in 150 m optical cavity (<< 3$^{\text{rd}}$ generation SR, ERL; >> high-gain FEL)
- X-ray power incident on crystal, $\sim 100 \text{ W}$ on 70 $\mu$ rms radius, appears to be manageable
  - Similar to undulators at 3$^{\text{rd}}$ generation sources
- Electron beam power is low:
  - $I=40 \mu\text{A (Q=40 pC)}$, $P_{\text{beam}}=0.3 \text{ MW}$
  - Energy recovery is not necessary in the accelerator
- $f_{\text{rep}}=100 \text{ MHz}$ with ERL?
  - Heating on crystals is an issue
  - Electron rms energy spread increases from 0.02 % to 0.05%
Ultra-Low Emittance Injector
( P. Ostroumov, Ph. Piot, KJK)

- The requirements for XFELO beams
  - Normalized rms emittance < 0.1 mm-mr
  - Bunch charge=20-40 pC
  - Bunch length(rms)=1-2 ps
    → Peak current >10 A
  - Energy spread < 1.4 M eV
  - Bunch rep rate > 1 MHz

- The ERL injector in high coherence mode (Cornell) satisfy the requirements

- A novel type of injector is being developed
The LCLS Injector has already Demonstrated the Bunch Performance---Need to Make 1 MHz Rep Rate!

Commissioning of the LCLS Linac and Bunch Compressors*
A New Design based on Old Concept

Use thermionic cathode rather than photocathode
- Low emittance demonstrated for pulsed DC gun [1]
- Avoid difficulties with photocathode drive laser in stability & uniformity
- Avoid space charge degradation at low energy

Use a VHF cavity considered for photocathode application[2], cut out a short portion of each period, and condition the pulse

1 – RF cavity with thermionic cathode (r=300 m), 100 MHz, 5 cm gap, 1 MV
2 – chicane, energy filter (.45 ns, Q=45 pC)
3 – horizontal jaw slits
4 – quadrupole triplet
5 – short solenoid
6 – monochromator of the beam energy, f=600 MHz
7 – sub-harmonic pre-buncher, f=300 MHz
8 – booster linac section, f=400 MHz (20 MeV)
9 – RF cosine-chopper to form rep. rate 1 MHz to 100 MHz (at 13 m)
10 – bunch compressor – I (5 m)
11 – SC linac section, 460 MeV, f=1300 MHz (20 MV/m, to 460 MeV)
12 – bunch compressor – II (5 m)
13 – main SC linac, f=1300 MHz (20 MV/m, to 1.6 GeV)
VHF Gun Cavity (LBNL[2] scaled to 100 MHz, Assume 1 MV)
Manual Optimization with TRACK

- This already satisfy the requirements
- Genetic optimization under way
Accelerator Configuration

- The current is low, therefore CW operation is feasible without energy recovery.

- However, the linac length/cost can be reduced significantly with recirculation.

- In a scheme with recirculation but without recovery, the injector energy can be chosen to be $>> 10$-20 MeV to eliminate the merger problem.
An XFEL O Facility Using a Recirculating SCRF Linac for Ultra-High Coherence and High Average Power

Q = 50 pC, $\varepsilon_0^* = 0.1 \mu$, $\Delta \tau \leq 5$ ps, $f \geq 3$ MHz
The Facility Can Also Be Operated in Ultra-Short Mode by Using a Different Injector

• A different optimization of the thermionic gun or
• Laser shaping to produce ellipsoidal beam
Concluding Remarks

- XFELO offers a new option for next generation light sources with several unique characteristics complementary to high-gain SASE:
  - High average spectral brightness
  - Narrow bandwidth
  - High rep rate > MHz

- An XFELO facility using a “Compact” recirculating SCRF linac with an ultra-low emittance injector appears to be feasible

- The facility may be operated in an ultra-short, SASE mode with a different injector